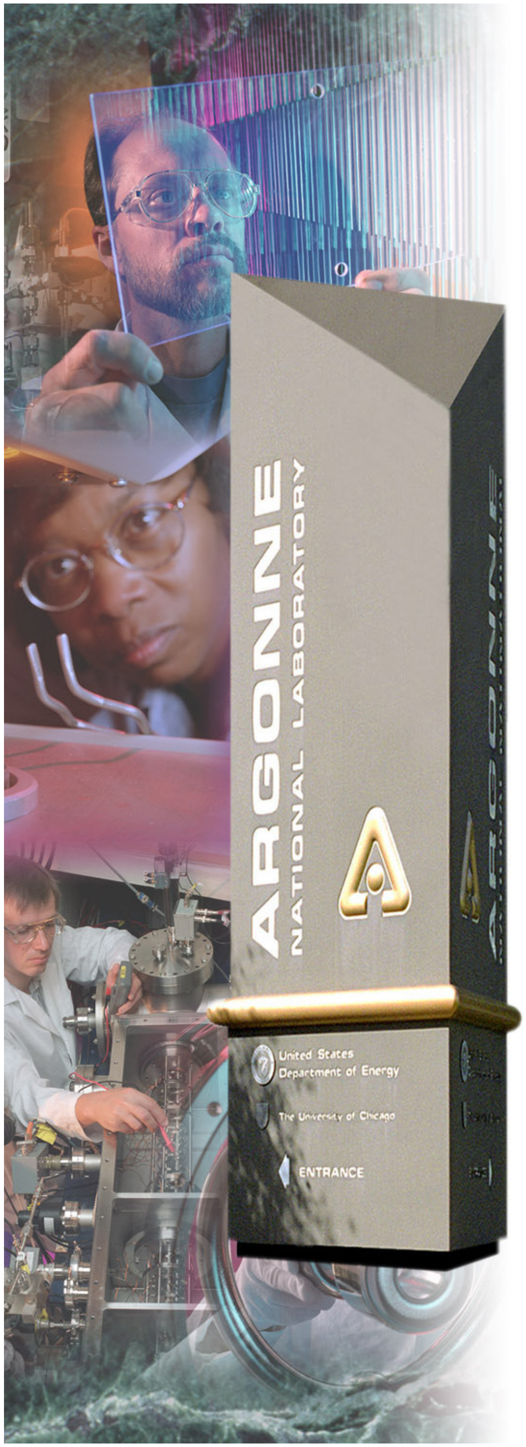

DANESS©

Dynamic Analysis of Nuclear Energy System Strategies

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Office of Science
U.S. Department of Energy

A U.S. Department of Energy
Office of Science Laboratory
Operated by The University of Chicago

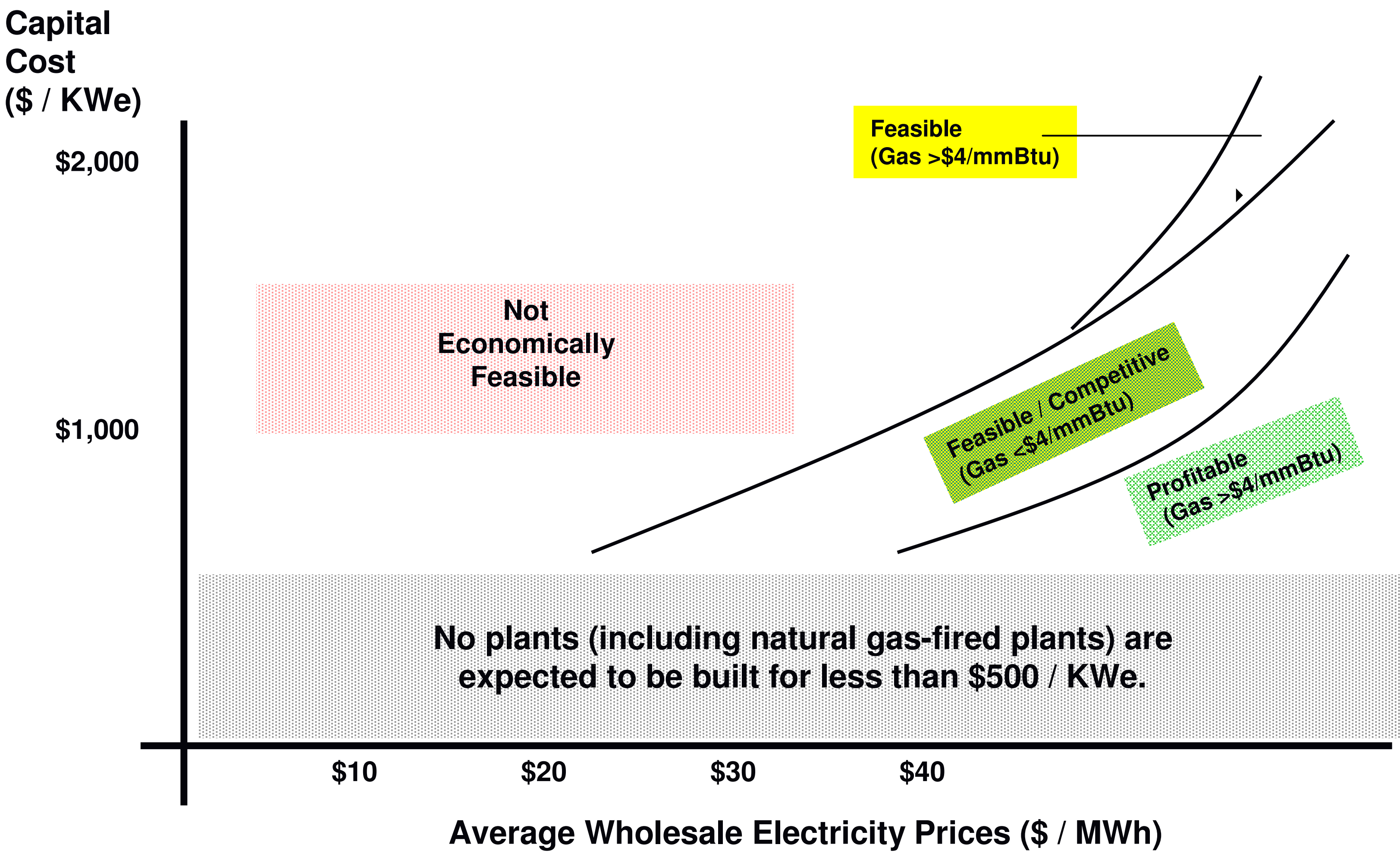
Overview of talk

- **The struggle for nuclear energy**
- **Motivation for research**
- **Objective for DANESS© development**
- **Overview of DANESS© -code**
- **Typical applications**
  - World reactor park
  - European Reactor Park
- **Future development**
  - LCA
  - Market penetration of nuclear and non-nuclear energy sources
    - *New energy markets (regional, energy vectors, ...)*
  - Non-proliferation
- **Conclusions**

The struggle for nuclear energy

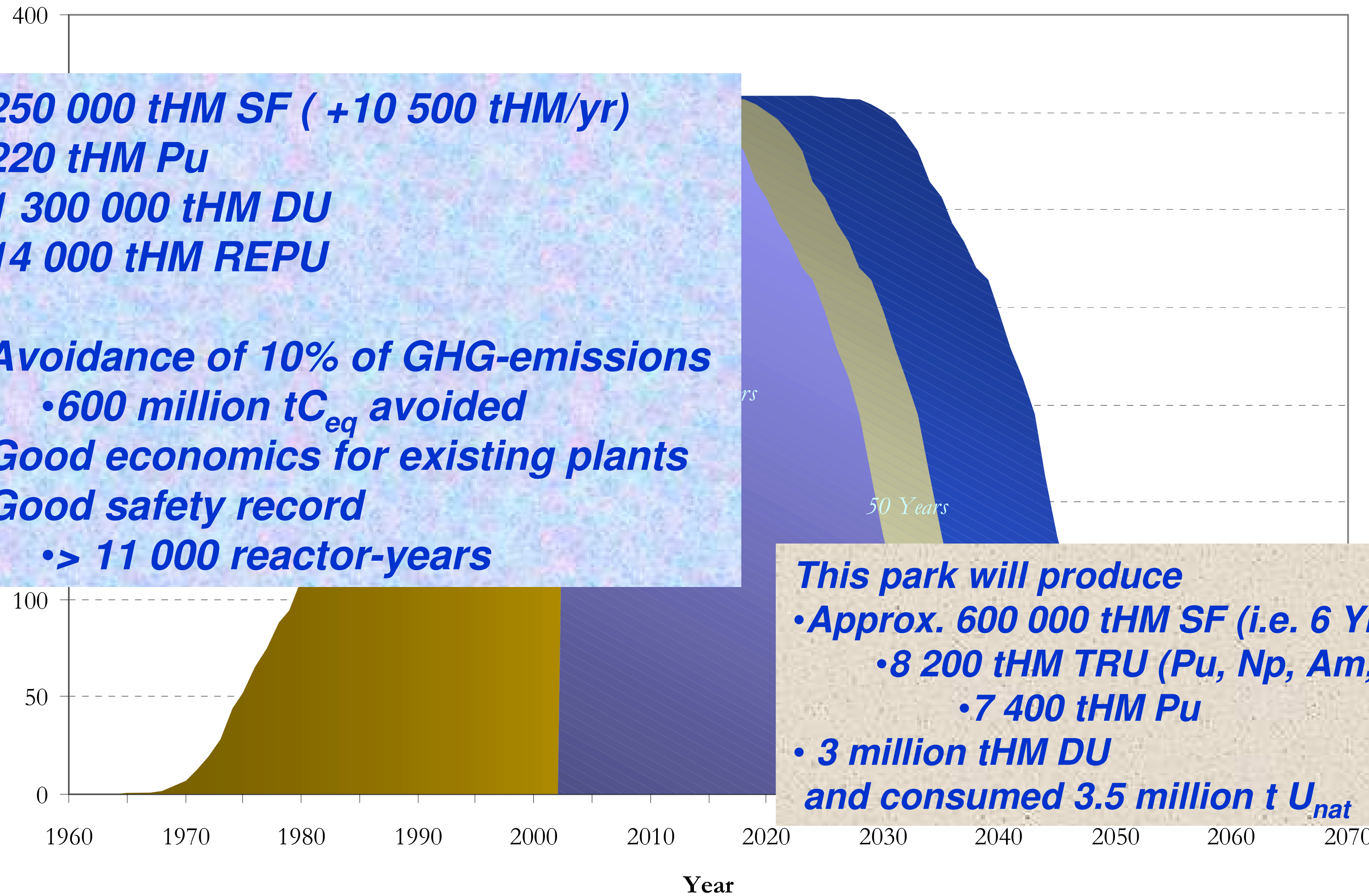
- **Existing nuclear power plants**
  - May be competitive in different markets
  - Are accepted by the public
  - Show a very good safety track record
  - But,
    - *Safety remains a concern*
    - *Fuel cycle issues are very important*
      - Waste management
      - Non-proliferation
- **New nuclear energy systems**
  - Should be competitive with evolved fossil-based and renewable energy sources
  - Should address the above concerns

Economics for new NPPs



Scully Capital Inc., 'Business Case for New Nuclear Power Plants', July 2002

Nuclear energy today



- *250 000 tHM SF (+10 500 tHM/yr)*
- *220 tHM Pu*
- *1 300 000 tHM DU*
- *14 000 tHM REPU*

- *Avoidance of 10% of GHG-emissions*
  - *600 million tC_{eq} avoided*
- *Good economics for existing plants*
- *Good safety record*
  - *> 11 000 reactor-years*

This park will produce
- *Approx. 600 000 tHM SF (i.e. 6 YME)*
  - *8 200 tHM TRU (Pu, Np, Am, Cm)*
    - *7 400 tHM Pu*
- *3 million tHM DU*

and consumed 3.5 million t U_{nat}

Changing environment

- **Public concerns with respect to climate change**
  - Recognises that fossil-based energy is not that good
  - Renewables hold potential but limited in capacity
  - Nuclear may address climate change issues and may deliver capacity, but public remains hesitant
- **Political agenda with respect to sustainable development**
  - Growing recognition
    - *That sustainable development demands political courage*
    - *That nuclear energy holds very strong potential to support sustainable energy systems*
- **Deregulated competitive markets**
  - Shift investment horizon from decades to years
  - Unbundling of activities in electricity markets
  - Growing infrastructure needs in developing countries

Motivation for Research

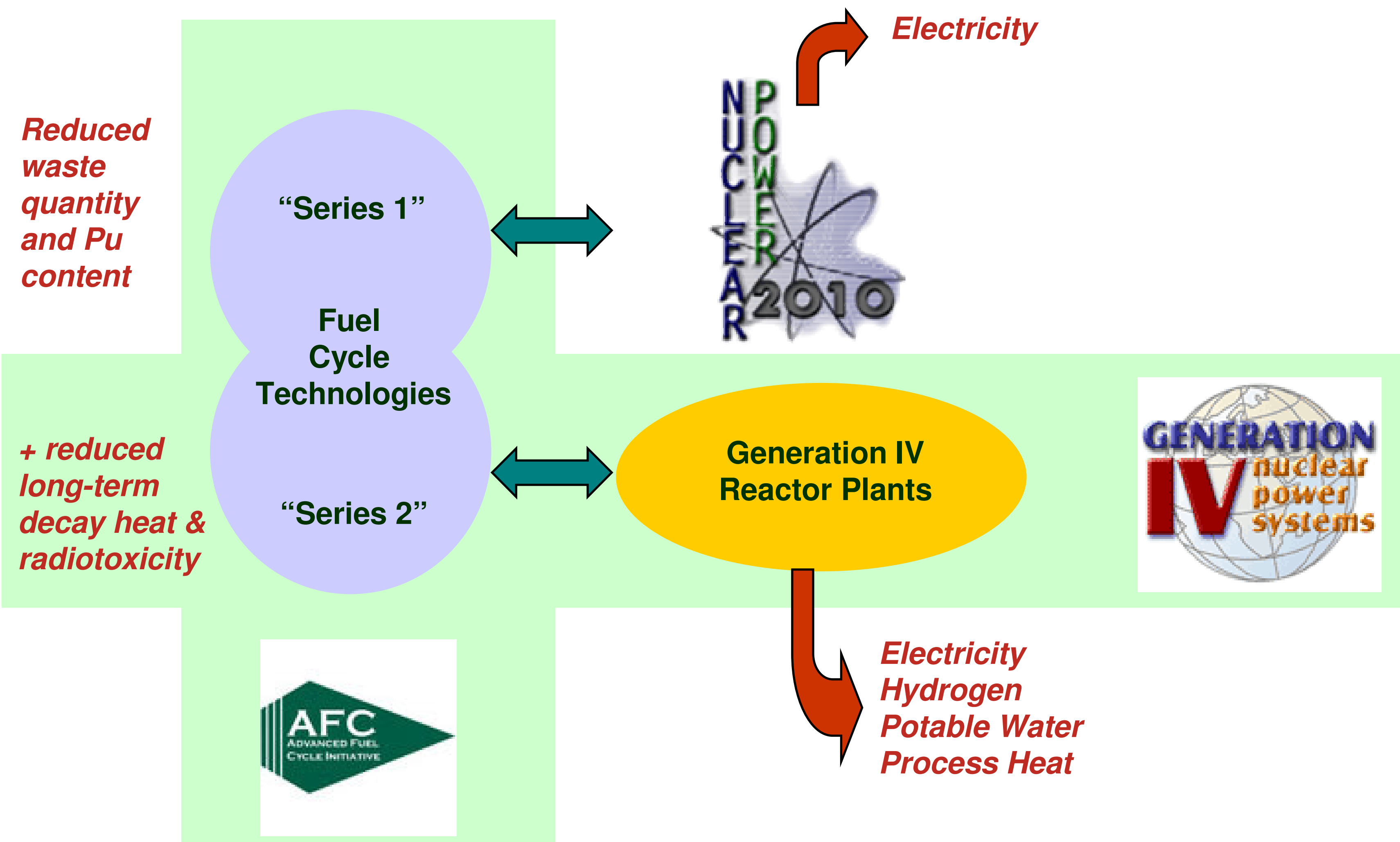
- **Economic competitiveness is essentially defined by reactors**
  - Trend towards evolutionary systems, i.e. risk mitigation
  - Struggle towards the < 1 200 US$/kWe range for overnight costs
- **Socio-political impediments for nuclear are essentially fuel cycle related**
  - Waste management
  - Non-proliferation
  - (Safety)
- **Policy view moved from strictly energy security towards energy security and sustainability**
  - *Sustainability of nuclear energy is defined by symbiosis between reactors and fuel cycle technologies*

What are drivers for this research?

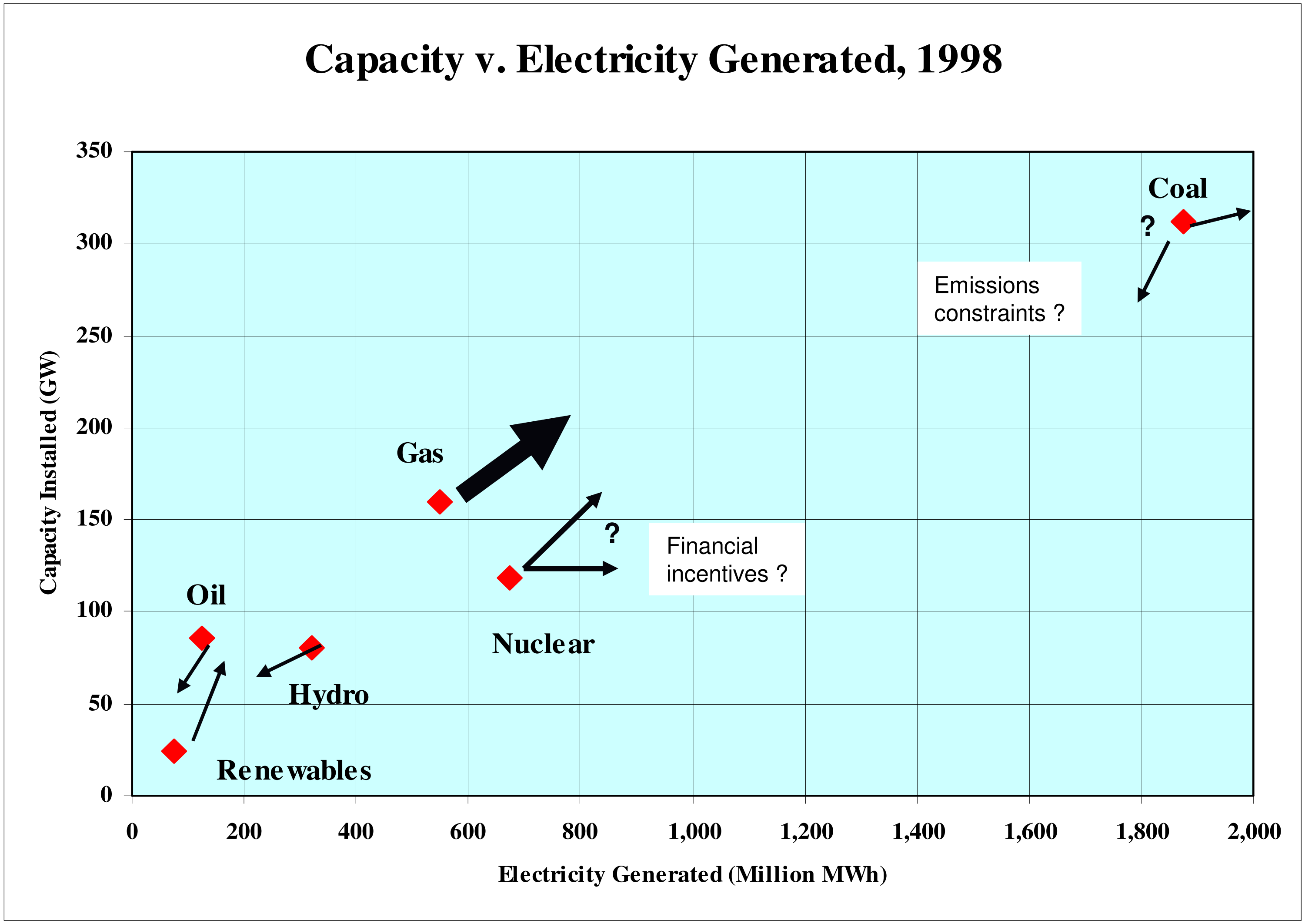
- **Technology push versus market pull**
  - Nuclear R&D makes shift today
- **Market defines future of energy systems**
  - But how to merge short-term interests with long-term concerns?
- **Nuclear energy is no universal magic solution**
  - Regional and technological different markets to be recognised
  - Does new energy vectors indeed deliver new scope?
  - Government play a crucial role in drafting the path forward

- **Tools needed to grasp this multi-disciplinary framework**
  - Integrated process models
- **Policy-informing is of growing importance**
  - Nuclear expertise may get lost in governments
  - Education needs for students, experts, policy-makers, …

Motivation for research (ctd.)



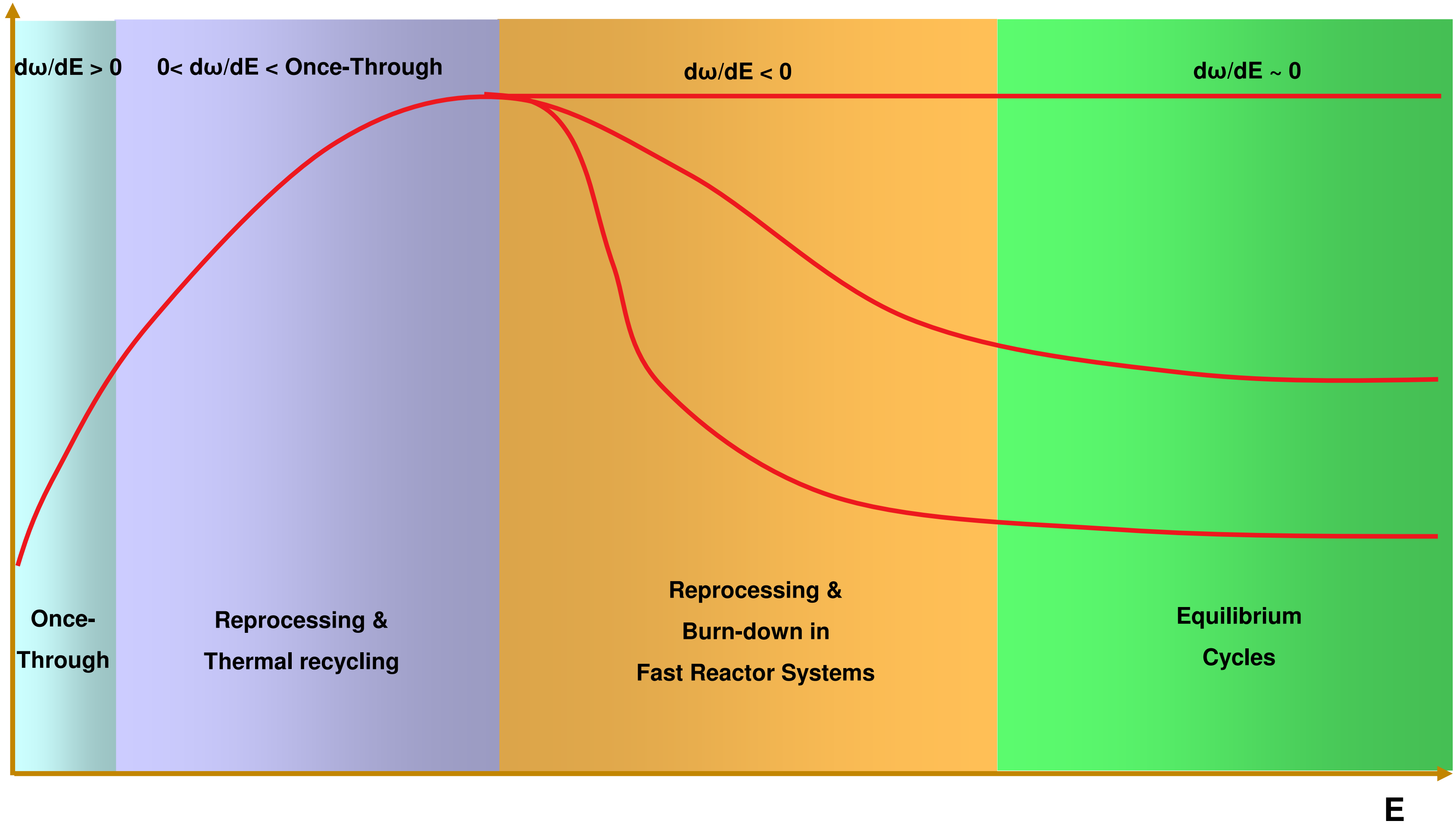
The path forward for installed capacity?



Source: DOE/EIA

Possible phases in nuclear energy development

ω = f(volume, radiological risk, short-term heat load, long-term heat load, TRU inventory ,...)



Goals for nuclear energy systems

- **Cap the amount of SF**

  Reprocessing

  - *Limit to 0.6 million tHM SF, i.e. amount accumulated from today's reactor park by 2050*
    - Equivalent to 6 repositories at regional fuel cycle centers
- **Minimize the volume of repository space needed for each additional TWh energy**

  Remove the actinides from waste

  - *Limit heat load in repositories*
- **Make it economically attractive**
  - *Limit fina*

  Allocate fissile materials for maximum added value
- **Serve the different energy markets**
  - *All*

  Deploy different reactors and regional fuel cycle centers
- **Manage non-proliferation concerns**

  Minimize out-of-pile inventories and use institutional frameworks
- **Drastically reduce the long-term stewardship of waste**
  - *From > 100 000 years to less*

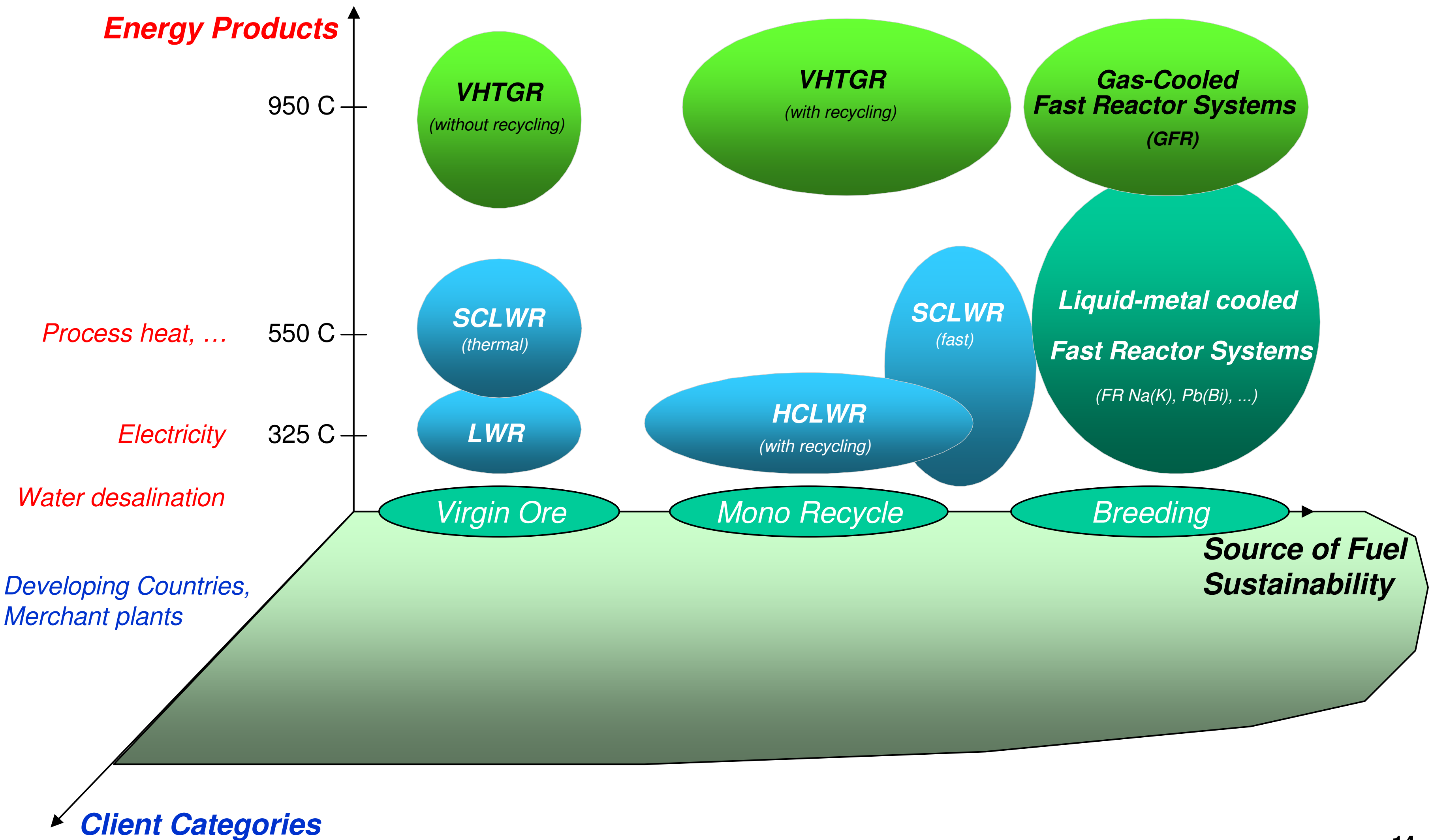
  Remove the actinides from waste

Main question for research

- ***What are possible ω-evolutions at a reasonable cost for utilities and government ?***
  - *Policy-informing tool needed to address this question*

- **Answering this question asks for insight in:**
  - Use of symbiosis among reactors and fuel cycle options
  - Energy market penetration potential for nuclear energy
    - *Competition with non-nuclear and new (niche) energy markets, e.g. Hydrogen*
    - *Externalities*
  - Socio-political impediments
    - *Waste management*
    - *Non-proliferation*
    - *Safety*
    - *LCA*

Multiple new NPP concepts are available

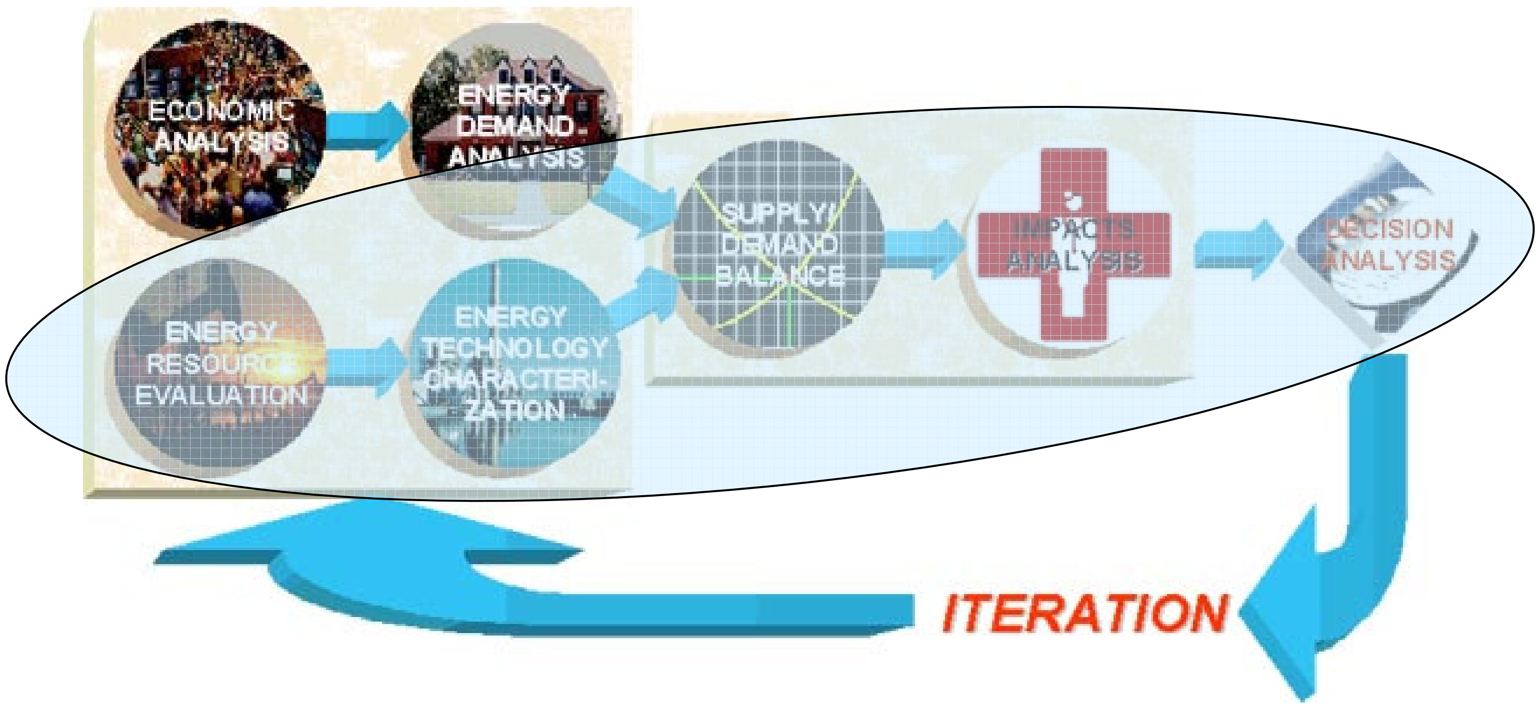


Objective for DANESS© development

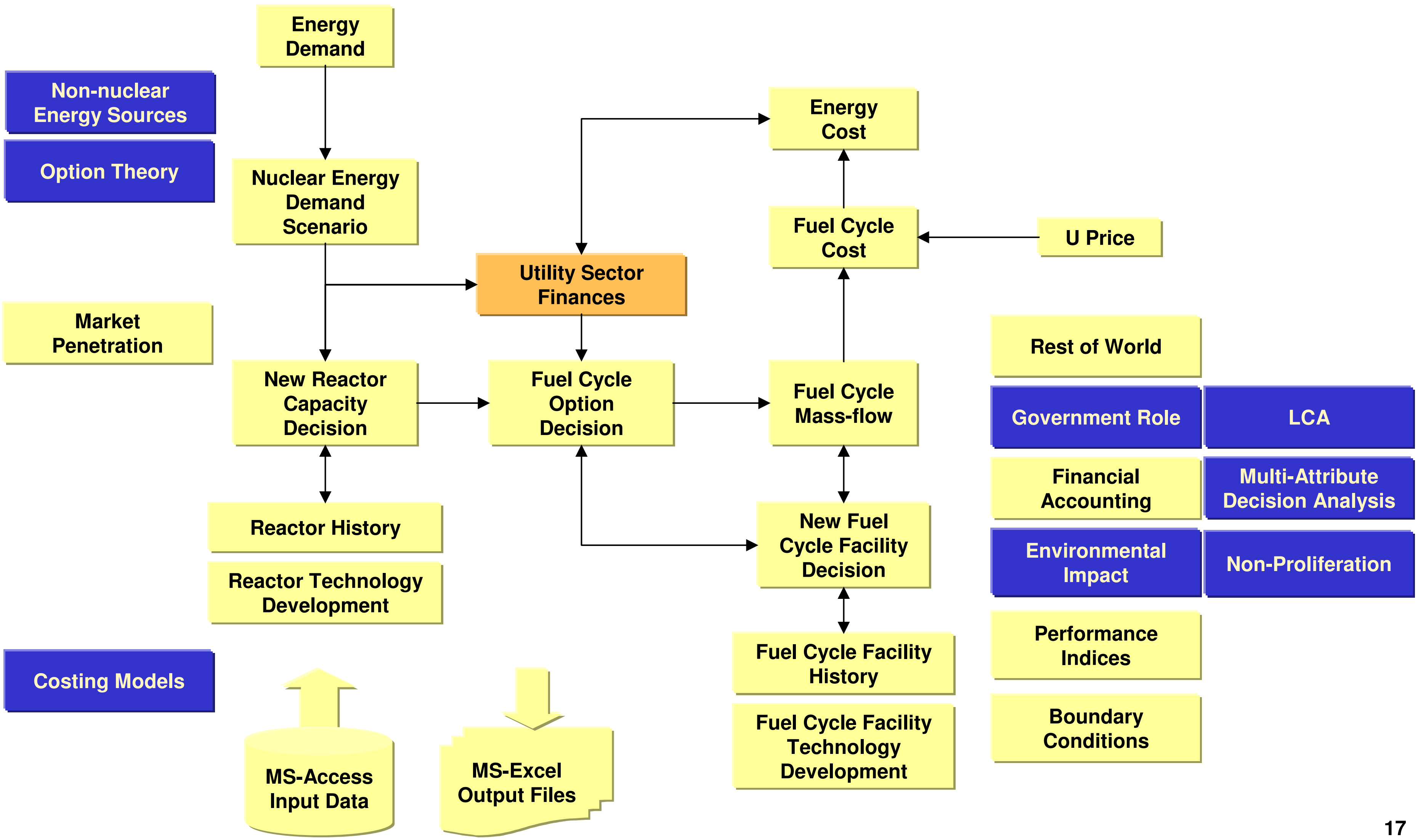
An easy-to-use and quick policy-informing tool
for the
technical-economic assessment
of nuclear energy systems
in a
macro-economic energy development context

- *Scope:*
  - *Integrated process model of nuclear energy systems*
  - *Integration with other energy model codes*
  - *PC/Mac platform, < 10 min calculation time*
  - *For use by experts, consultants, policy-makers, students, …*

Today, DANESS© is an Intra-nuclear model



DANESS© v1.0



Energy Demand
Non-nuclear Energy Sources
Option Theory
Nuclear Energy Demand Scenario
Energy Cost
Fuel Cycle Cost
U Price
Utility Sector Finances
Market Penetration
Rest of World
New Reactor Capacity Decision
Fuel Cycle Option Decision
Fuel Cycle Mass-flow
Government Role
LCA
Financial Accounting
Multi-Attribute Decision Analysis
Reactor History
New Fuel Cycle Facility Decision
Environmental Impact
Non-Proliferation
Reactor Technology Development
Performance Indices
Costing Models
Fuel Cycle Facility History
Boundary Conditions
Fuel Cycle Facility Technology Development
MS-Access Input Data
MS-Excel Output Files

Positioning of DANESS©

Outside Look

Macro-Economic Energy Models

MARKAL
AMIGA
ENPEP
EMCAS
…

Technical-Economic Model

combining

Fuel Cycle Analysis
Economics
Macro-economic factors
Environmental factors
Socio-political factors

COSI
SEMER
NFCSim
MEEMS/OSIRIS
SuperStar

Inside Look

Existing Codes

REBUS-3
ERANOS
SCALE
…

BEST4/5, CONCEPT, DISCOUNT-G, FAPMAN-ORSIM, GEM, KOSAK, KPD, ORCOST, POWERCO, SCENARIOS, SOTHIS

Functionalities of DANESS© v1.0

- **Nuclear energy demand driven**
- **Reactor history model, i.e. up to 10 reactor types**
- **Detailed fuel cycle massflow model, i.e. up to 10 fuel types**
  - All fuel cycle steps modeled
  - Crossflow of fissile material between fuel types, i.e. reactor types
  - Combinations may be varying over time, i.e.
    - *Reactor / Fuel use*
    - *Fuel / Fuel Cycle Facility use*
- **Economics**
  - Levelized costing
  - Cashflow analysis
  - Intra-nuclear market penetration model
- **Waste Management**

Features

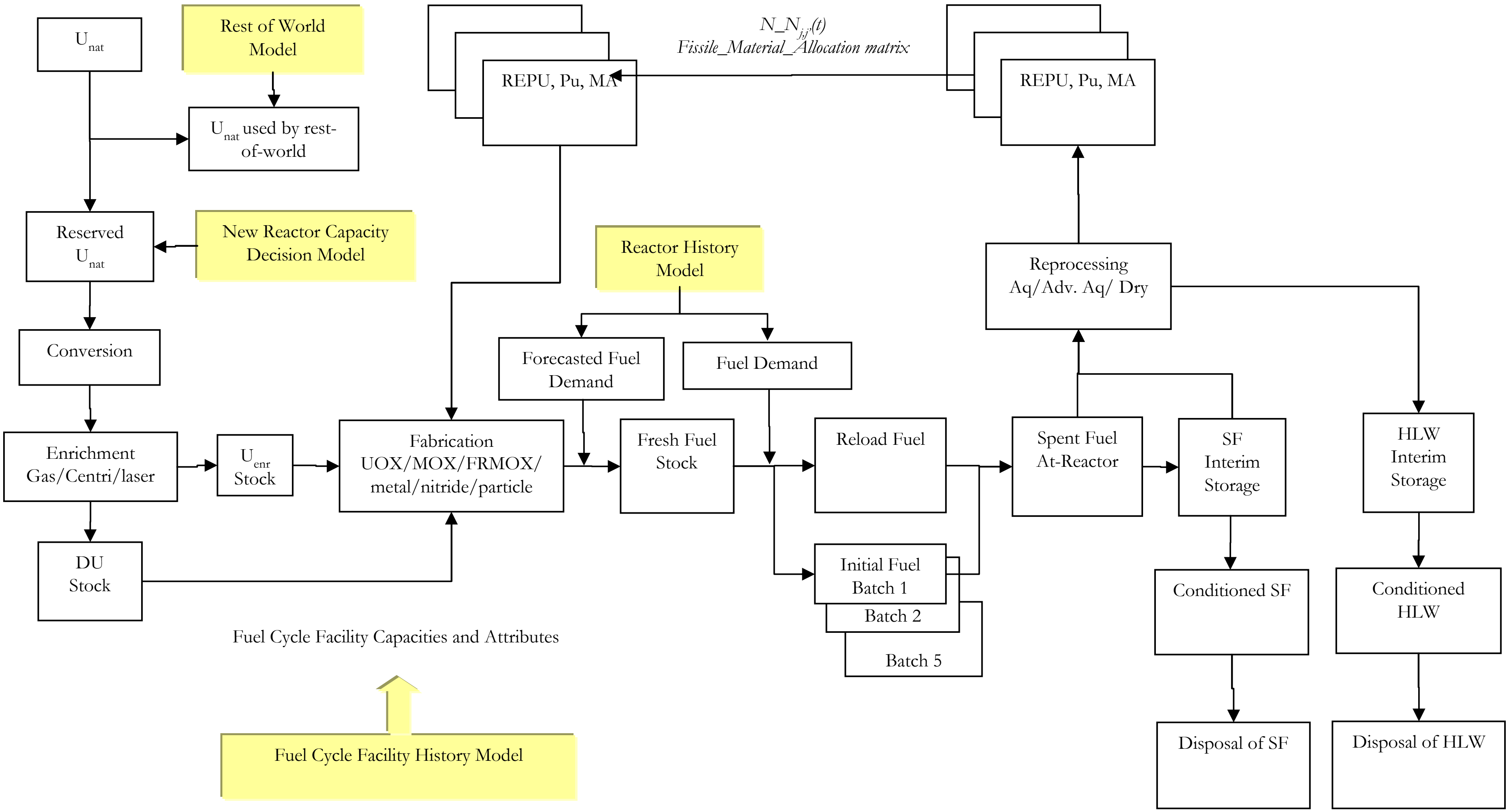
- **Developed using commercial software Ithink (www.hps-inc.com)**
  - Possibly other software environments in nearby future
- **May be web-based**
- **Easy-to-use**
  - ‘Get-to-know’-time: approx. 2 weeks
  - ‘Repeat-to-know’-time: one hour
  - Can be customized / parametrized
    - *Parametrized models available for World / USA / Europe / …*
- **Supported by database**
  - Attributes Reactors / Fuels / Facilities
  - Allows up-to-date simulations

DANESS©

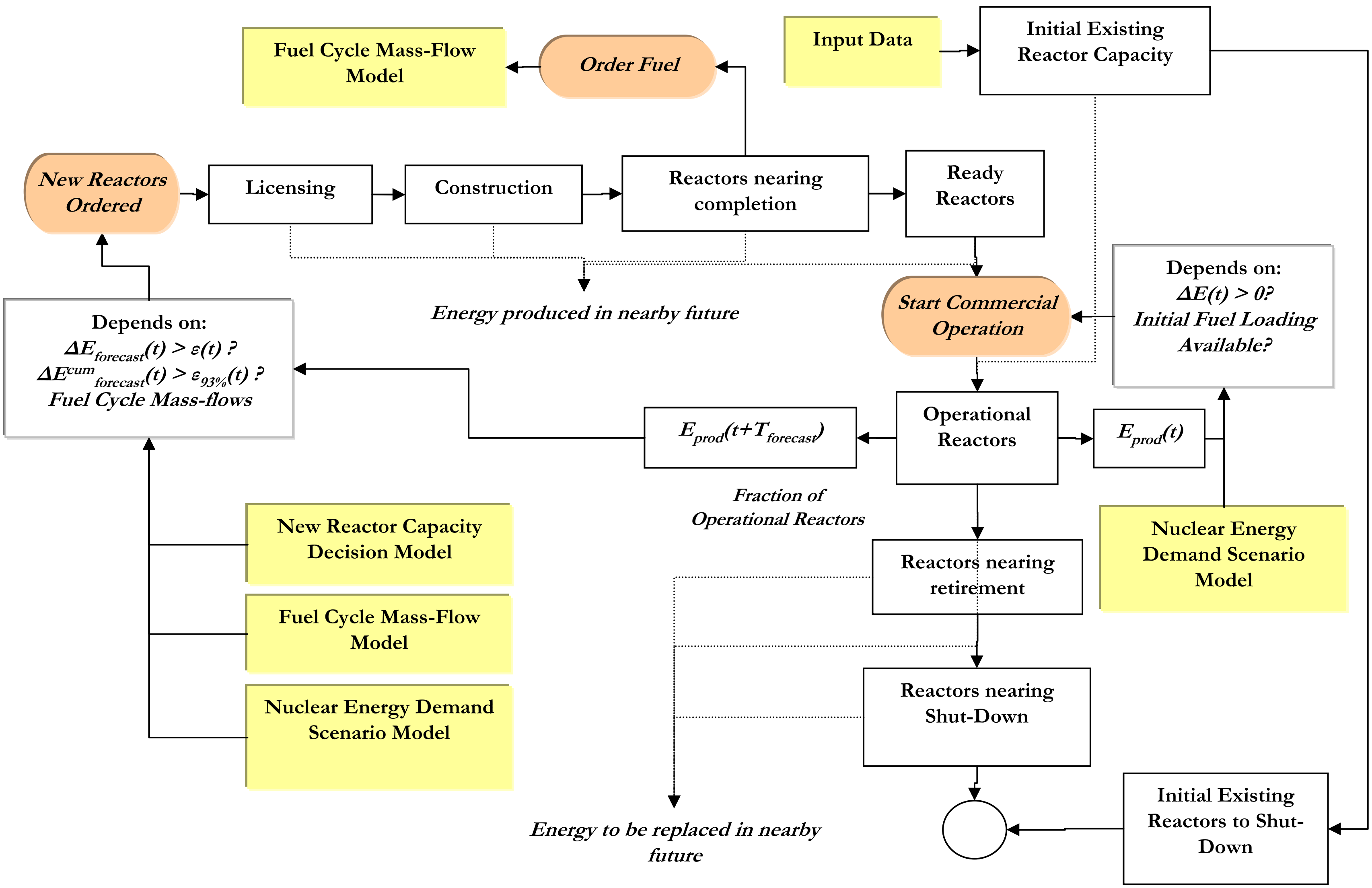
- **Users Group arrangement**
  - Share source code + co-development
  - Database support
  - Newsgroup / Discussion forum
  - Sharing of expertise / applications / benchmarking
- **Training**
  - Training set available
- **Additional information**

www.daness.anl.gov

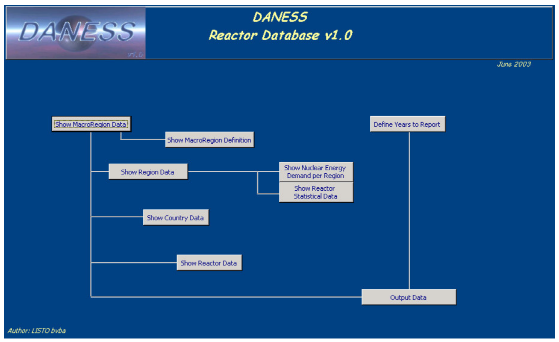
Schematics of fuel cycle model



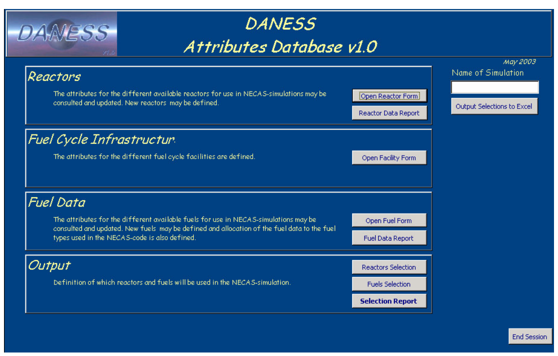
Schematics of reactor history model



Coupled databases



- **History of existing and planned reactors**
  - Including statistics
  - Annually updated



- **Attributes of reactors, fuels and fuel cycle facilities**
  - Including references
  - Regularly updated

Typical capabilities of DANESS©

- **Nuclear energy system scenario analysis**
  - Steady-state
  - Transient
- **Sensitivity analysis of reactor / fuel / facility characteristics**
  - Trade-off studies BU / repro-yield / …
  - Delays in technology availability
- **Economic analysis**
  - Levelized costing
  - Cashflow analysis for investment decisions
  - Government expenses / support actions
- **Multiple energy products demand**
  - Symbiosis between sustainability objectives
    - *energy vectors / reactors / fuels / …*

Future Developments

- **DANESS© = a *socio-technical-economic* model**

- **Today, DANESS© is rather complete as nuclear IPM, i.e.**
  - *Technical* dimension of model is developed
- **Work is undertaken to improve the *economic* part**
  - Market penetration model
    - *Collaboration with ANL/CEESA (ENPEP, EMCAS, ...)*
  - But also need to look into externalities
  - LCA
- **Future work is needed on *socio-political* part**
  - Non-proliferation
  - Other socio-political incluences on technical and economic dimension.

DANESS© Development Chart

	Socio	*Technical*	*Economic*
Mass flows	✓	✓	✓
Market Penetration		✓	✓
Non-nuclear energy sources		<u>✓</u>	<u>✓</u>
Technology Development		✓	✓
Waste Management	<u>✓</u>	✓ / <u>✓</u>	<u>✓</u>
Non-proliferation	<u>✓</u>	<u>✓</u>	
Life Cycle Assessment	<u>✓</u>	<u>✓</u>	<u>✓</u>
Detailed flowsheets processes		<u>✓</u>	<u>✓</u>

✓ = implemented; <u>✓</u> = to be done or under development

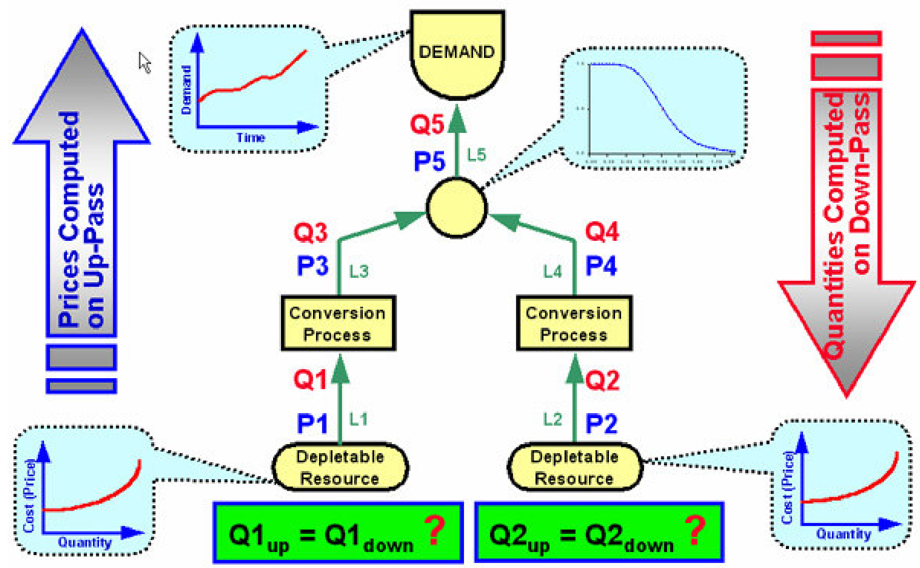
Intended Use

- **Analysis of development paths for nuclear energy**
- **Integrated process model**
- **Parameter scoping for new designs**
- **Economic analysis of nuclear energy systems**
- **Government role**
- **Educational use**

Market penetration

- **Collaboration with ANL/CEESA: ENPEP-BALANCE**

- **Non linear equilibrium matching demand with available resources and technologies**
- **Respons of various segments of market to changes in price and demand**



Life Cycle Analysis

- **Objective:**
  - In order to address ‘all’ socio-technical-economic issues in the assessment of nuclear energy develoment, account must be take of:
    - *Primary and secondary material streams during*
      - Construction,
      - Operation,
      - Decommissioning
        - And in normal and abnormal circumstances
    - *Associated costs, some of those being external to today’s costing practices*
- **Integration of LCA-capability in DANESS**
  - All basic information (timings, mass flows, ...) are available
    - *Add-on of LCA functionality*

LCA (ctd.)

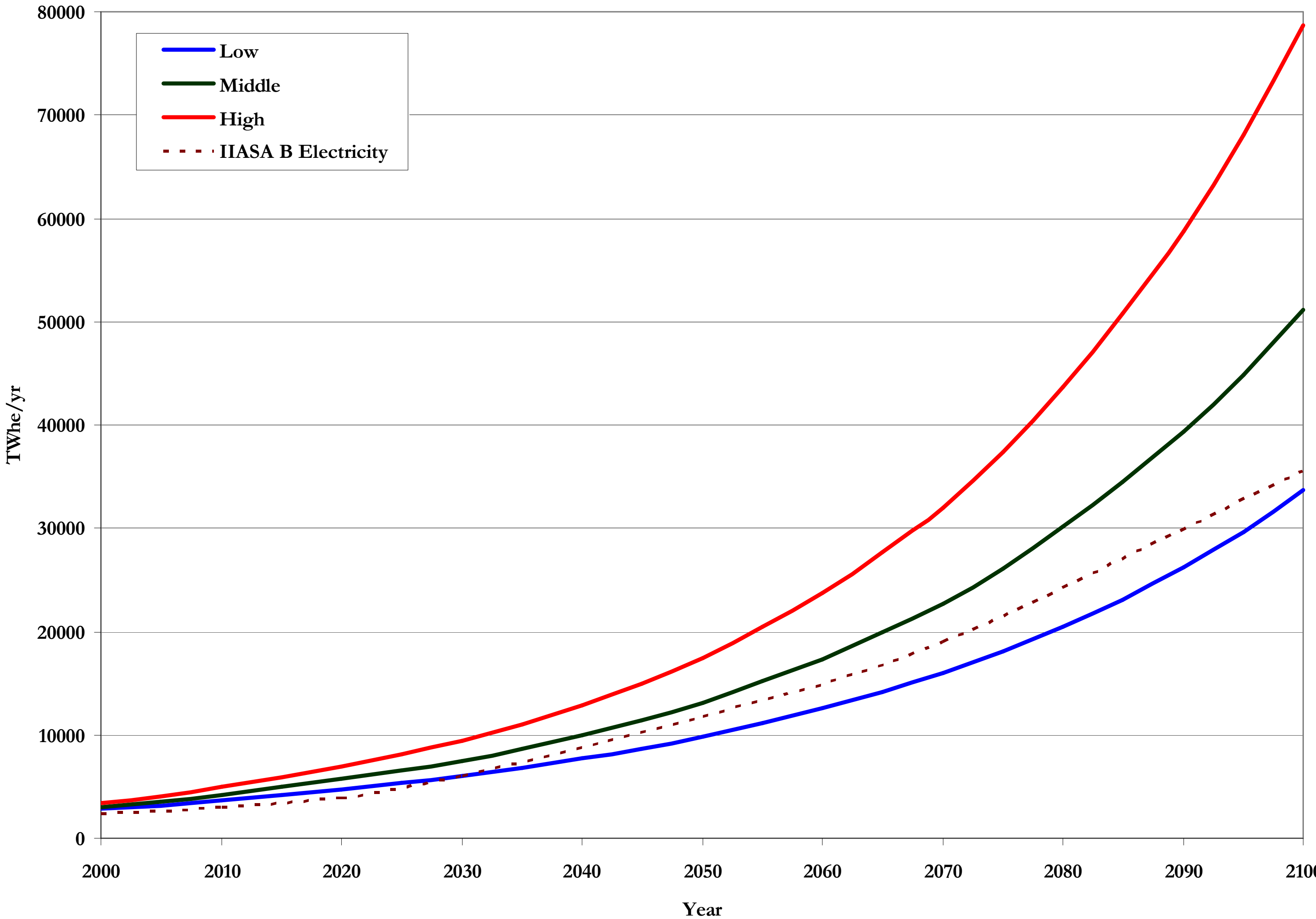
- **LCA-functionality for intra-nuclear options requests:**
  - Data based on experience feedback for existing technologies
  - Expert judgement needed for new technologies (reactors & fuel cycle facilities)

- **Activities to be undertaken:**
  - Check Ecoinvent methodology and compatibility with DANESS
  - Compose database of LCA-data in accordance to DANESS model
    - *Initially based on existing and evolutionary technology*
    - *Need for expert judgement for more advanced technologies or options*
  - Translation of database into analytical projected LCA-data for intermediate cases

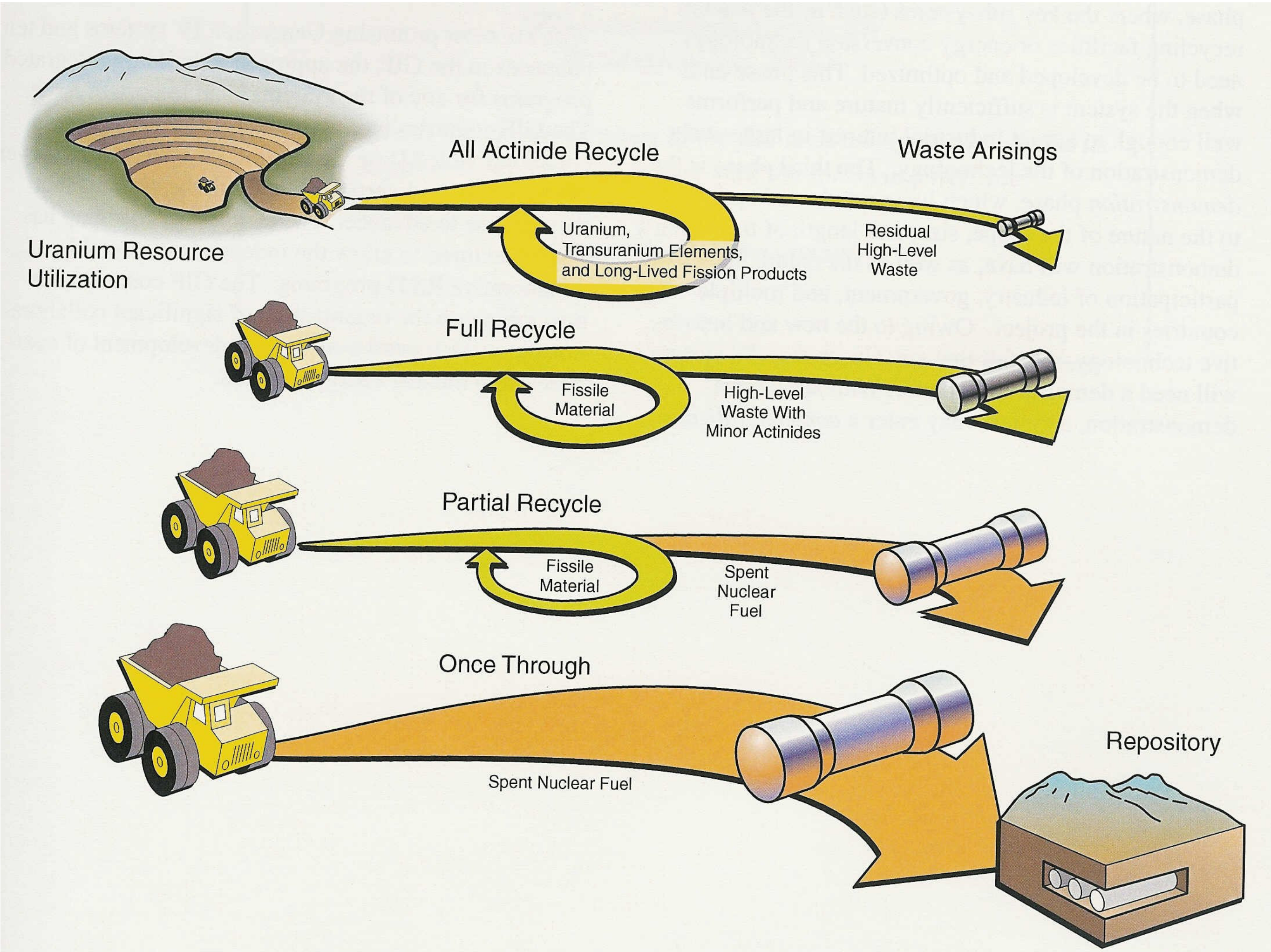
Typical applications

- **World**
  - OTC
  - MOX Pu mono-recycling
  - FR introduction
- **USA**
  - Elec + H_2 demand
- **European reactor park**
  - Business as usual (partial MOX continuation)
  - CORAIL introduction
  - IMF impact
  - FRs

Nuclear energy demand scenarios



Possible energy system scenarios



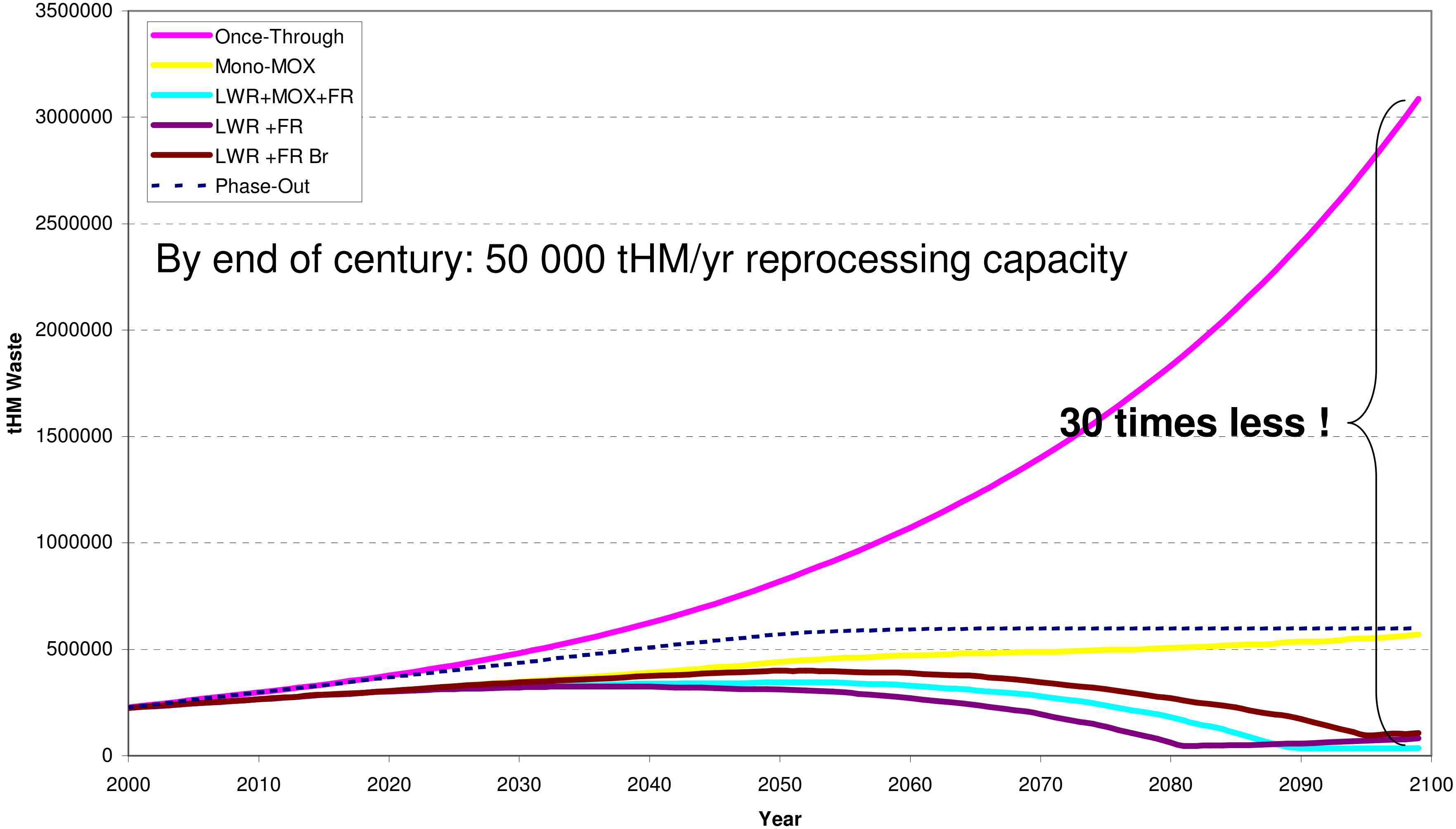
Closed Fuel Cycle
LWR + HTGR + FR
LWR + FR (breeder)

Multiple Pu recycling
LWR + HTGR
LWR + HTGR + FR

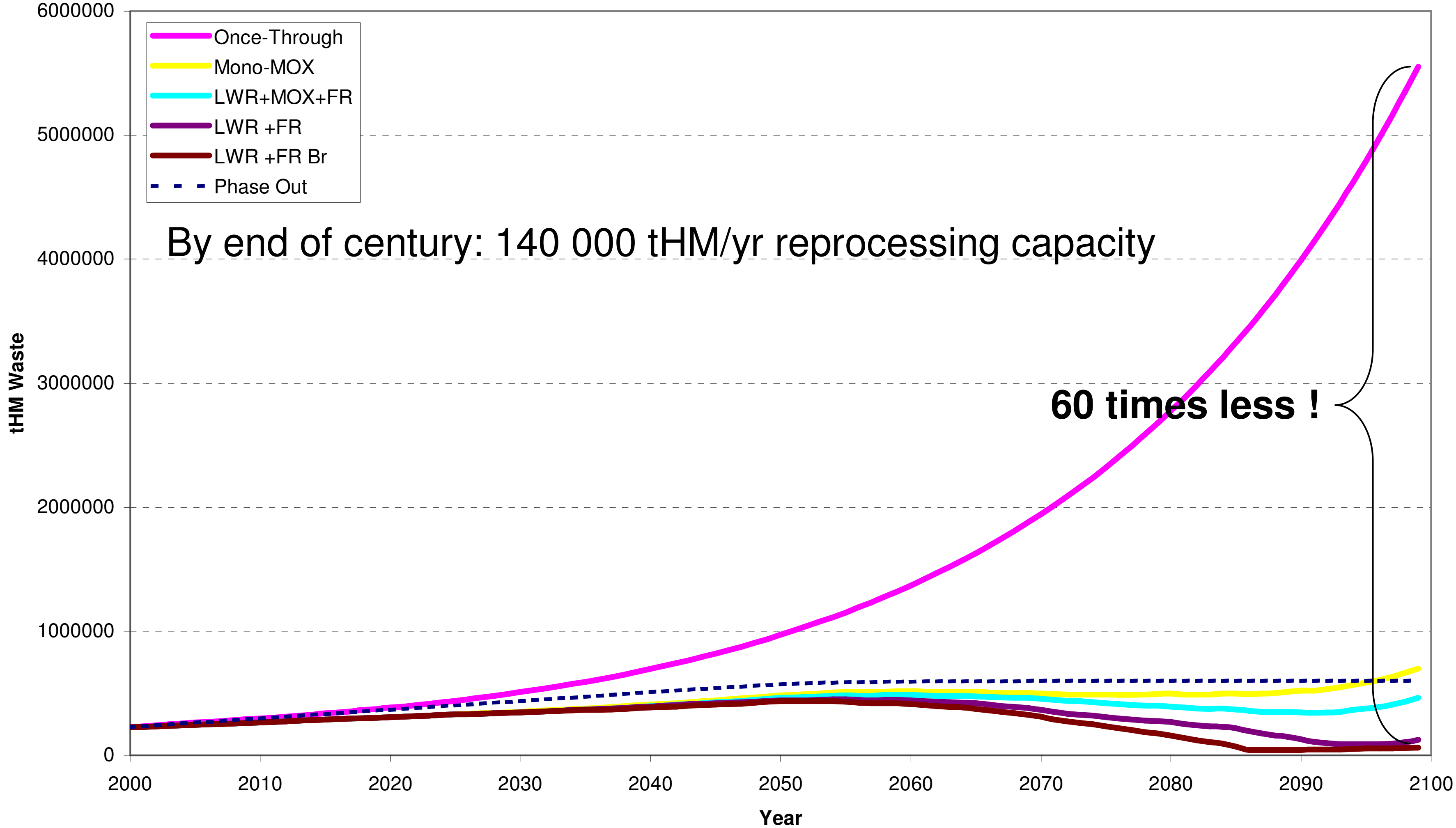
Mono Pu recycling
LWR + HTGR

Once-Through
LWR + HTGR

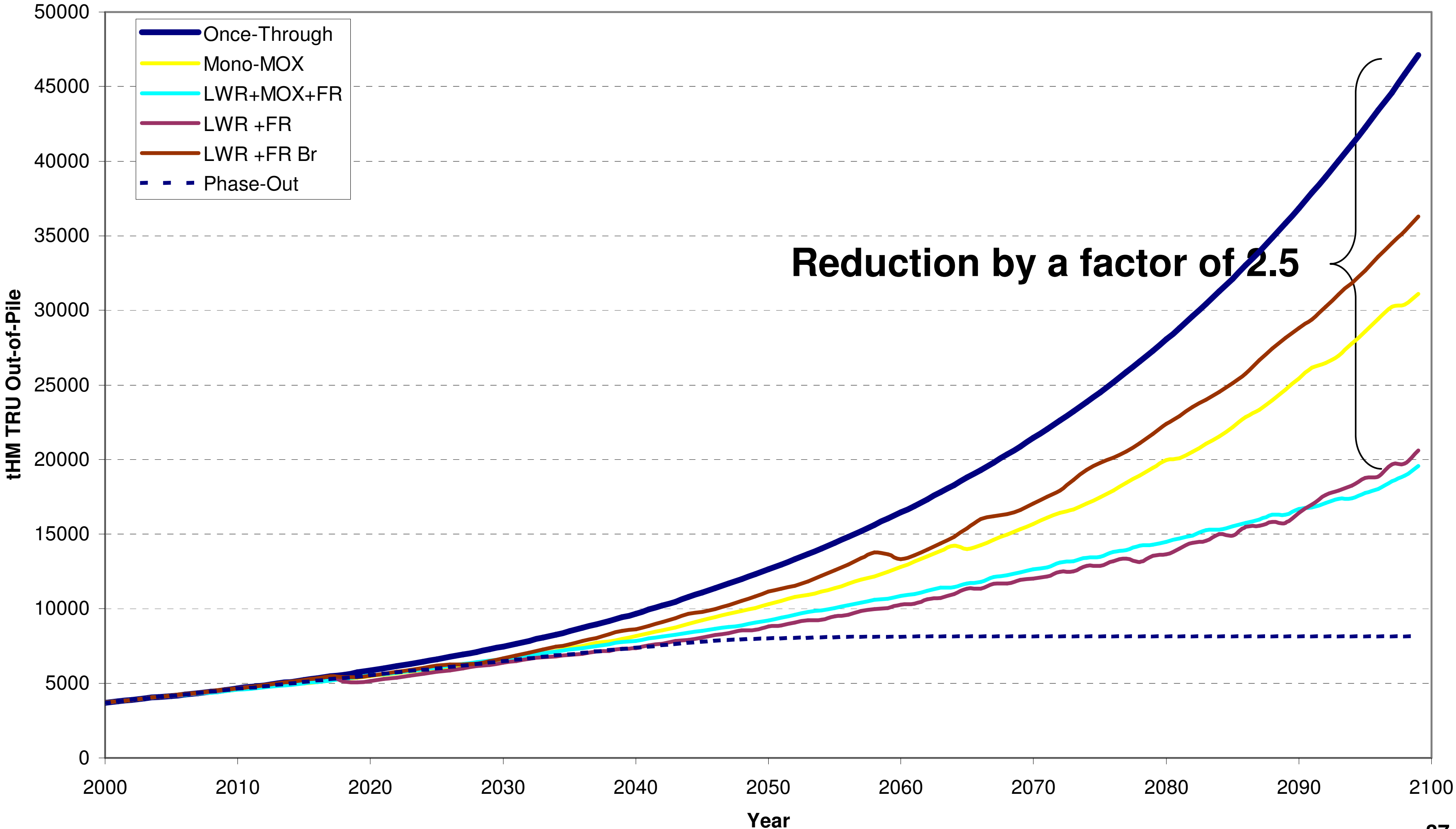
Amount of Waste Arising (Low)



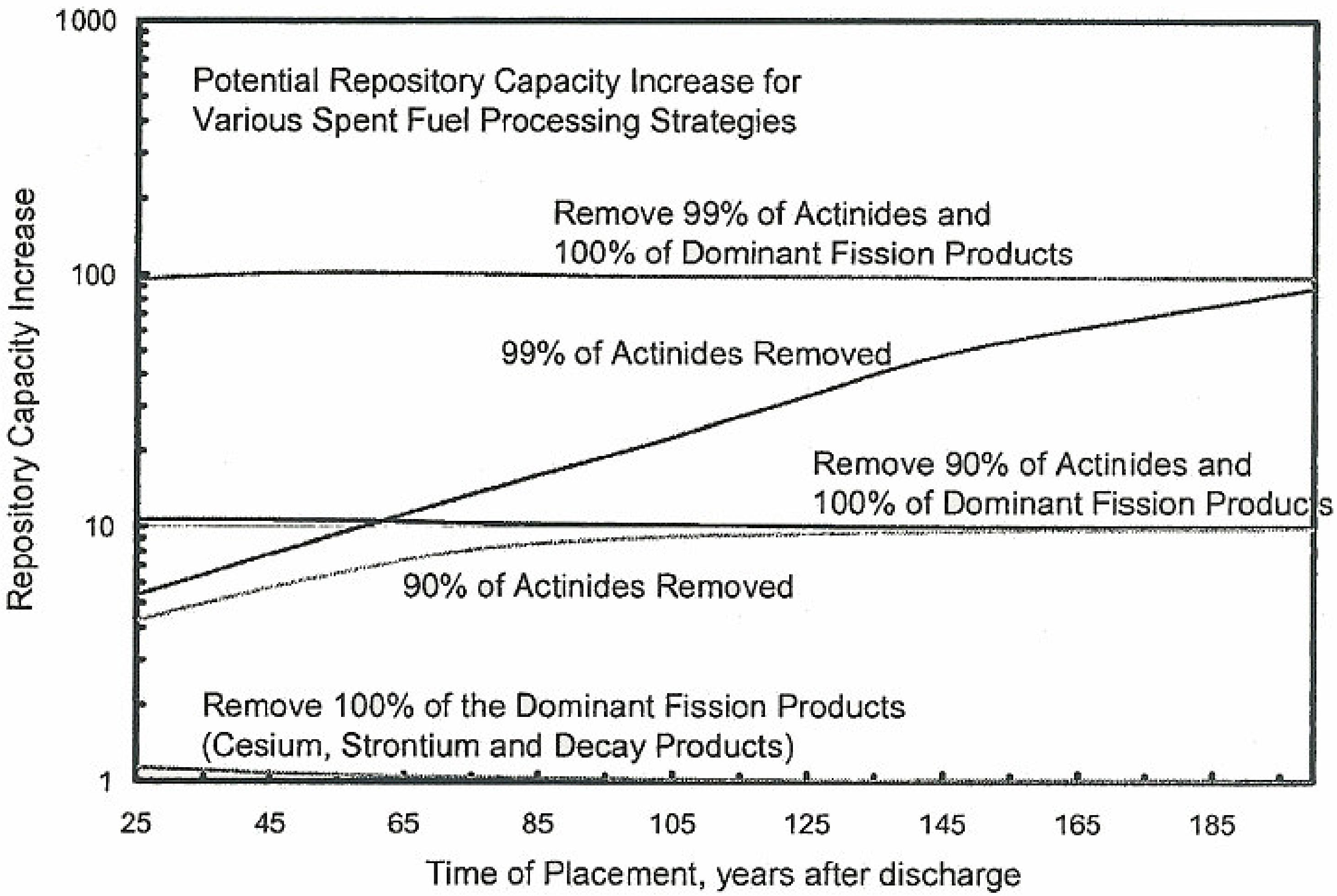
Amount of Waste Arising (High)



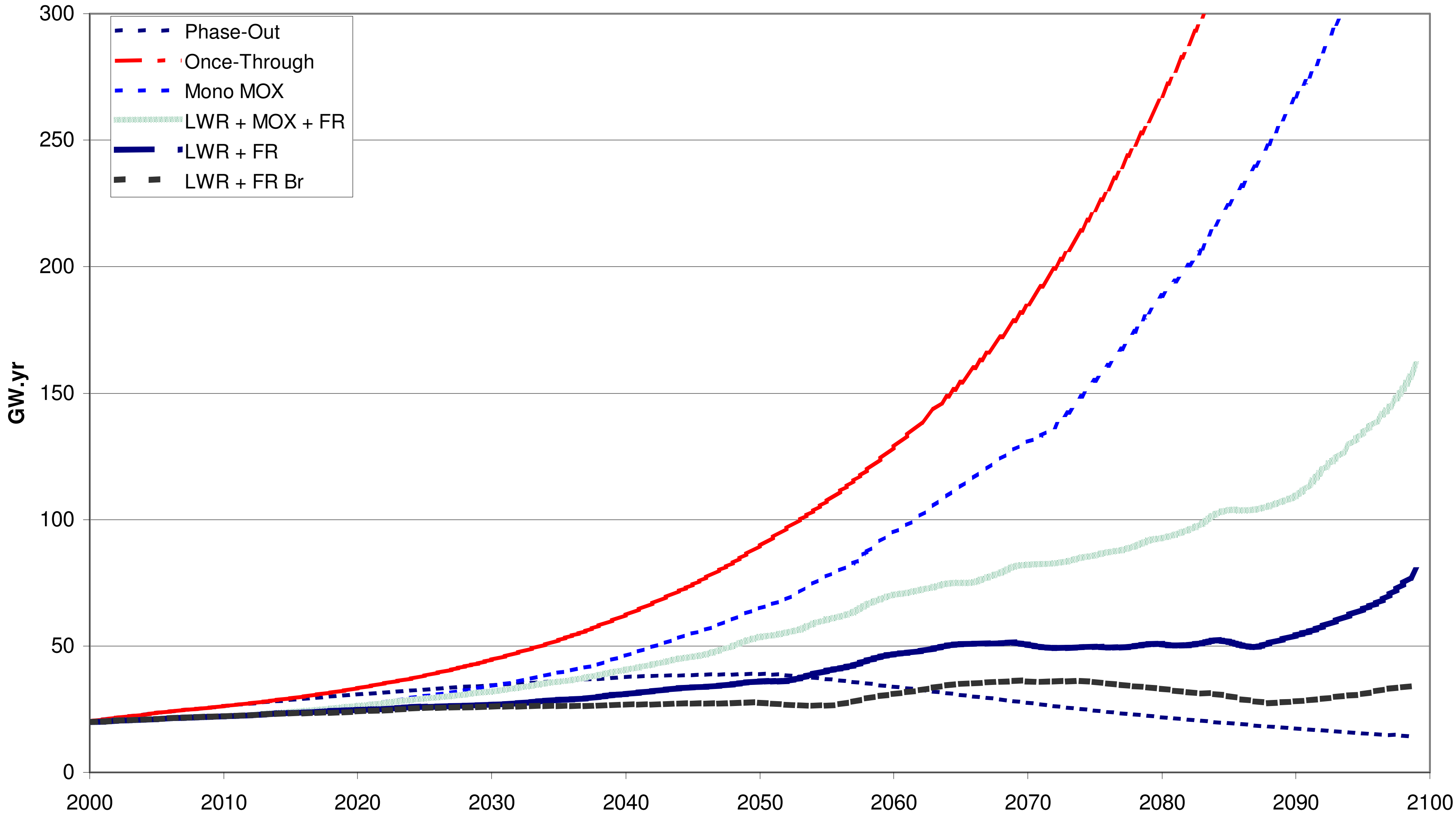
Amount of TRU Out-of-Pile (Low)



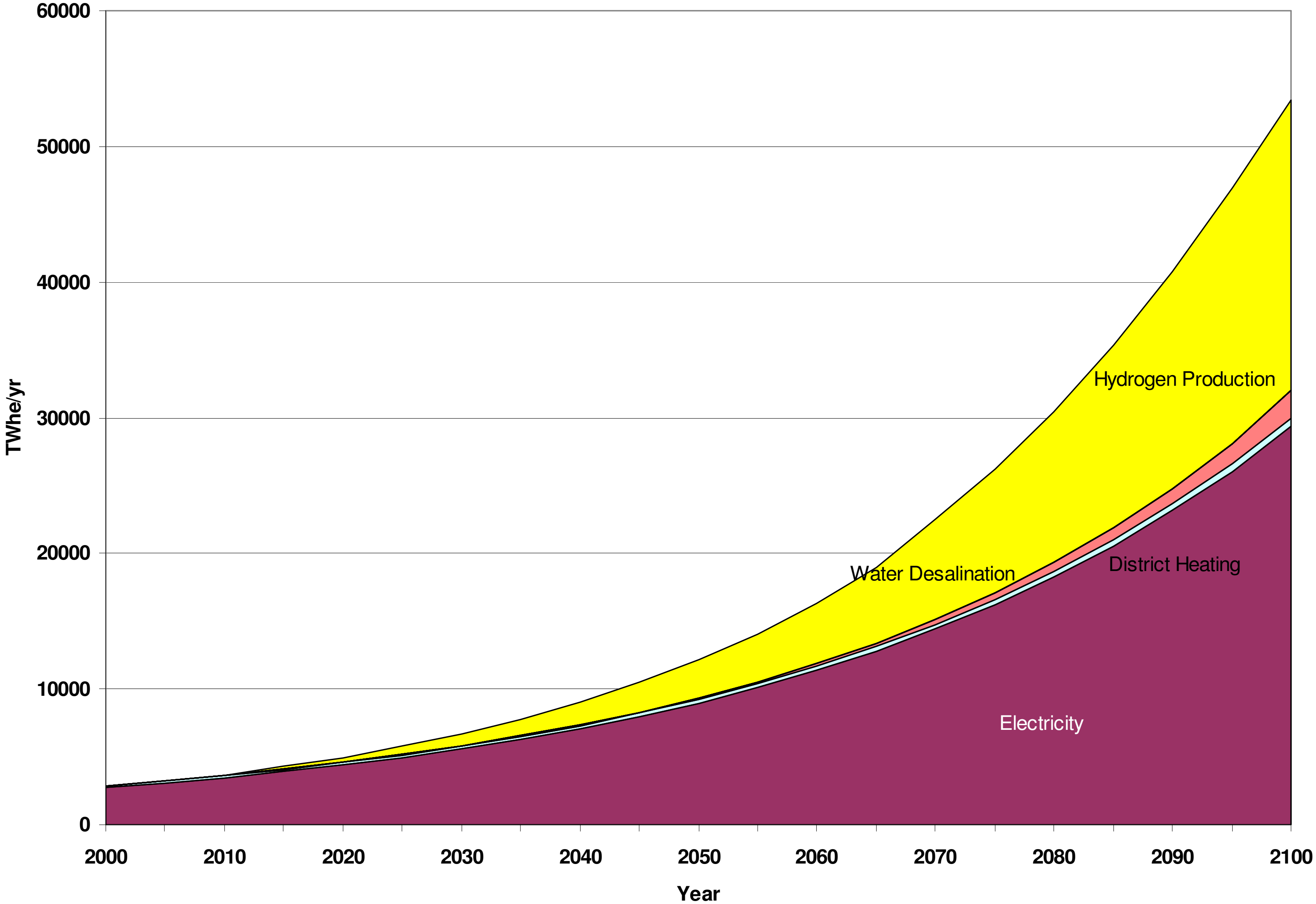
Actinide Removal is important



Heat Load to repository (High)



Reactor park matches energy demand

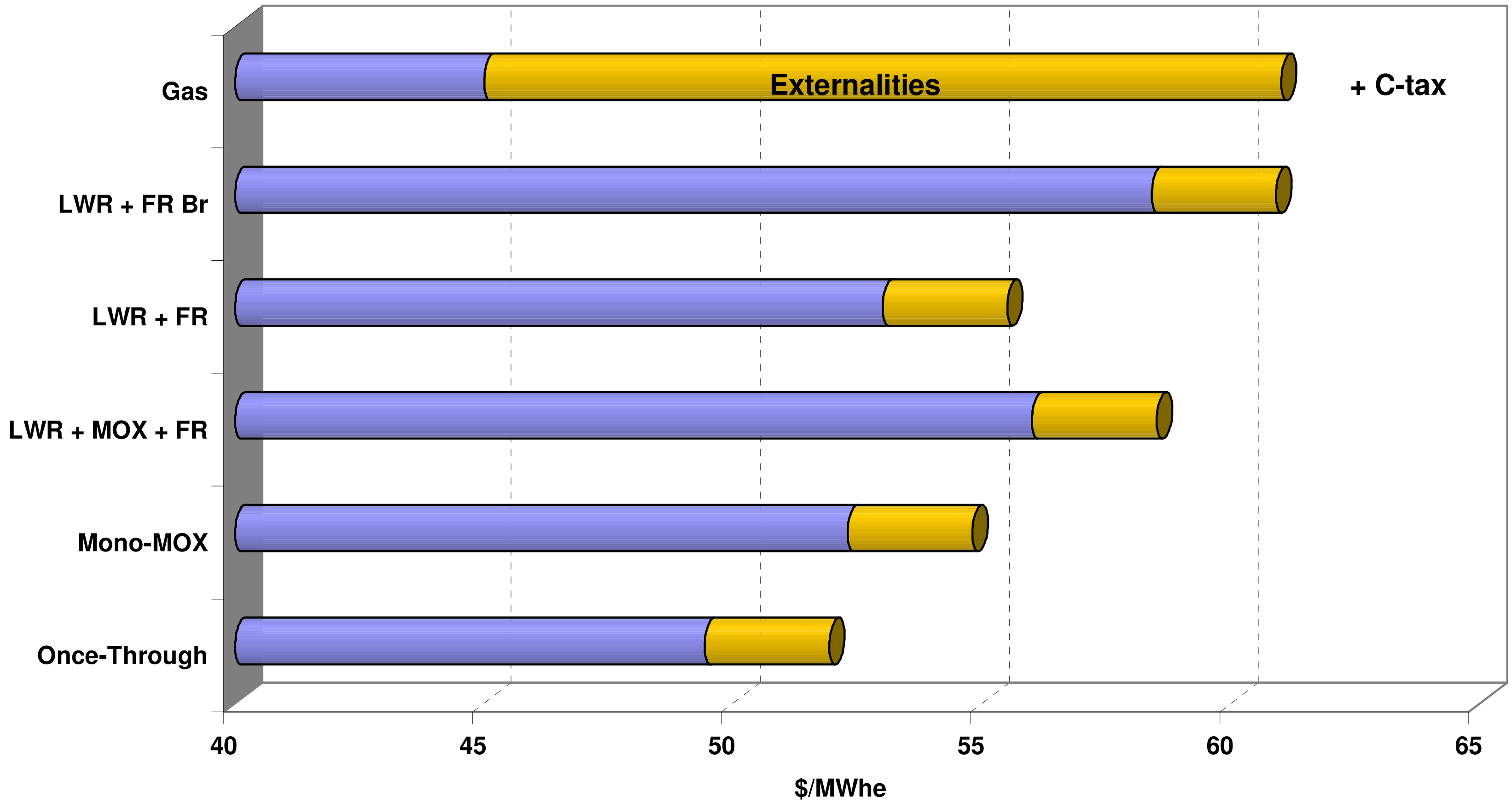


Summary World Scenarios

- **Vast amounts of energy may be delivered**
  - Minimal waste arising, i.e. waste amount limited to 0.5 million tHM
  - Number of repositories remains limited, e.g. 5 to 10 sites worldwide at regional fuel cycle centres
  - Reduce TRU inventory in fuel cycle by at least 50 %
  - Intrinsic non-proliferation barriers
    - *Strengthened by institutional set-up of regional fuel cycle centres*

- **What about the economics?**

Economics

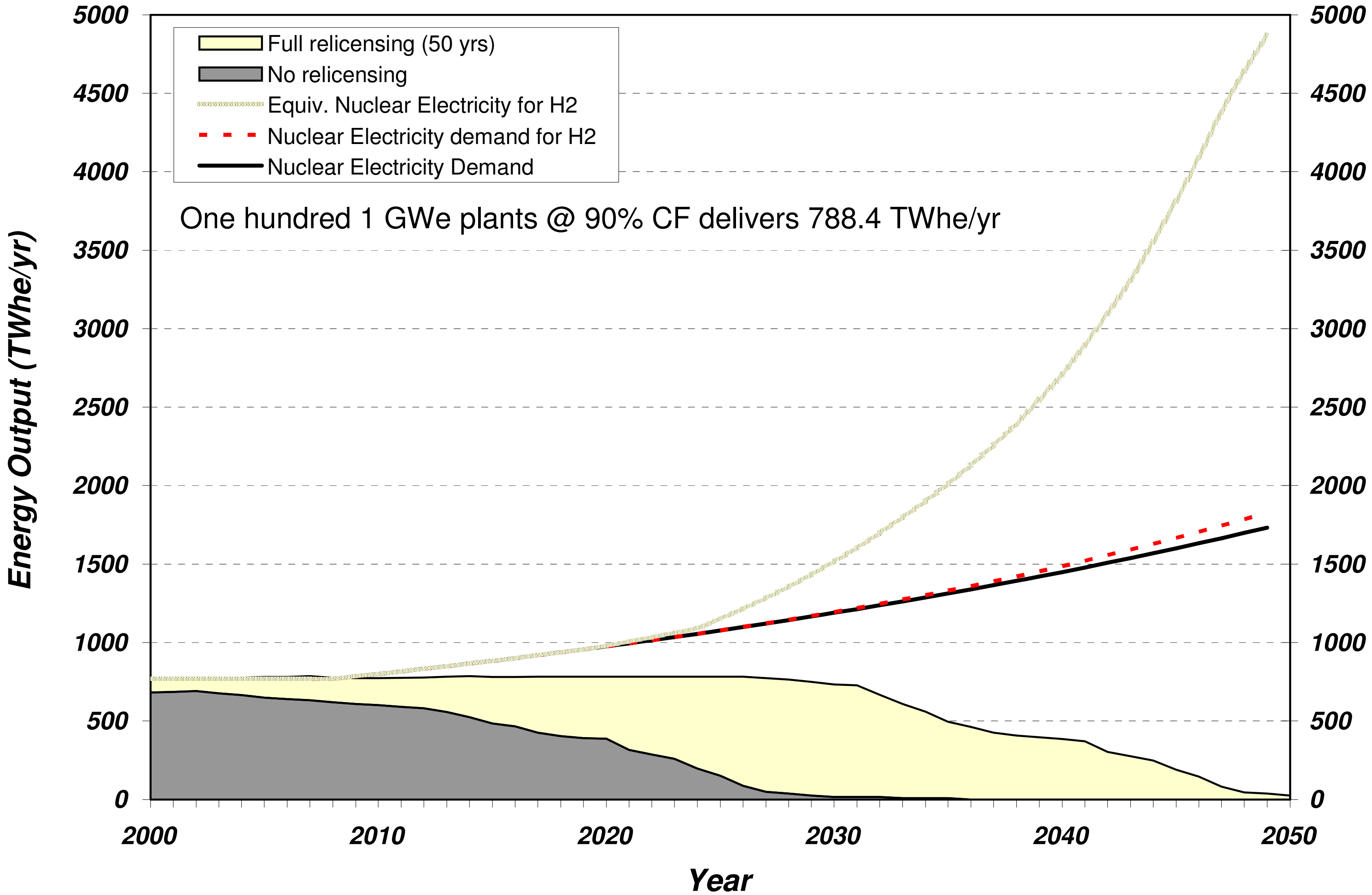


- Fuel cycle cost accounts for less than 1/5th of total cost
- Doubling of U-price results into a total cost increase by less than 5%

Electricity and Hydrogen demand scenario for the US

- **Based on DOE/EIA & IIASA/WEC data,**
  - Overall electricity demand
    - 2000-2020, growth by 1.9 %/yr
    - 2020-…., growth by 1.4%/yr
  - *Energy demand assigned to nuclear is expected to grow by 2 %/yr after 2010*
  - Overall hydrogen demand
    - 2000-2020, growth by 2.2 %/yr
    - 2020-…., growth by 1 to 1.6 %/yr depending on sector
      - 1 %/yr residential and transport sector
      - 1.6 %/yr refinery sector
      - 1.4 %/yr commercial sector
      - 1.5 %/yr industrial sector
  - *Nuclear hydrogen production assumed from 0% in 2020 to 25% by 2050*

Total Nuclear Energy Demand



Four fuel cycle scenarios considered

- LWRs in once-through mode
- LWRs + HTGRs in once-through mode
- LWRs + FRs CR>1
- LWRs + HTGRs + FRs (different CRs)

- LWRs essentially for electricity production
- HTGRs + FRs for hydrogen production

Reactor and Fuel Attributes

Reactors	**PWR**	**BWR**	**ALWR**		**HTGR**	**FR**		
Thermal Power (MW_{th})	2647	2647	2647		600	843		
Electric Power (MW_e)	900	900	900		284	320		
Thermal Efficiency (%)	34	34	34		47	38		
Capacity Factor (%)	90	90	90		90	85		
Technical lifetime (yr)	50	50	50		50	50		
						CR		
Fuels						0.25	0.5	1.25*
	UOX	**UOX**	**UOX**	**MOX**	**Particle**	**Metal**		
Average Burnup (GWd/tHM)	50	40	50	50	120	200	120	22
# fuel batches	5	5	5		3	7	7	3
Cycle length (mo)	12	12	12		12	12	12	12
Initial U (t/tIHM)	1	1	1	0	1	0	0	0
Initial enrichment (%)	4.2	3.7	4.2	0.25	15.5	0.25		
Initial DU (t/tIHM)	0	0	0	0.91903	0	0.0395	0.061	0
Initial REPU (t/tIHM)	0	0	0	0	0	0.3305	0.5936	0.9253
Initial Pu (t/tIHM)	0	0	0	0.08097	0	0.519	0.2919	0.0651
Initial MA (t/tIHM)	0	0	0	0	0	0.1117	0.0535	0.0009
Spent U (t/tIHM)	0.93545	0.94576	0.93545	0.88753	0.85917	0.3305	0.5936	0.8965
Spent enrichment (%)	0.82	0.8	0.82	0.15	4.8			
Spent Pu (t/tIHM)	0.012	0.1085	0.012	0.05512	0.01883	0.3769	0.2365	0.072
Spent MA (t/tIHM)	0.00125	0.00114	0.00125	0.0074	0.002	0.0897	0.0452	0.0077
Spent FP (t/tIHM)	0.0513	0.04225	0.0513	0.04996	0.12	0.2029	0.1248	0.0238

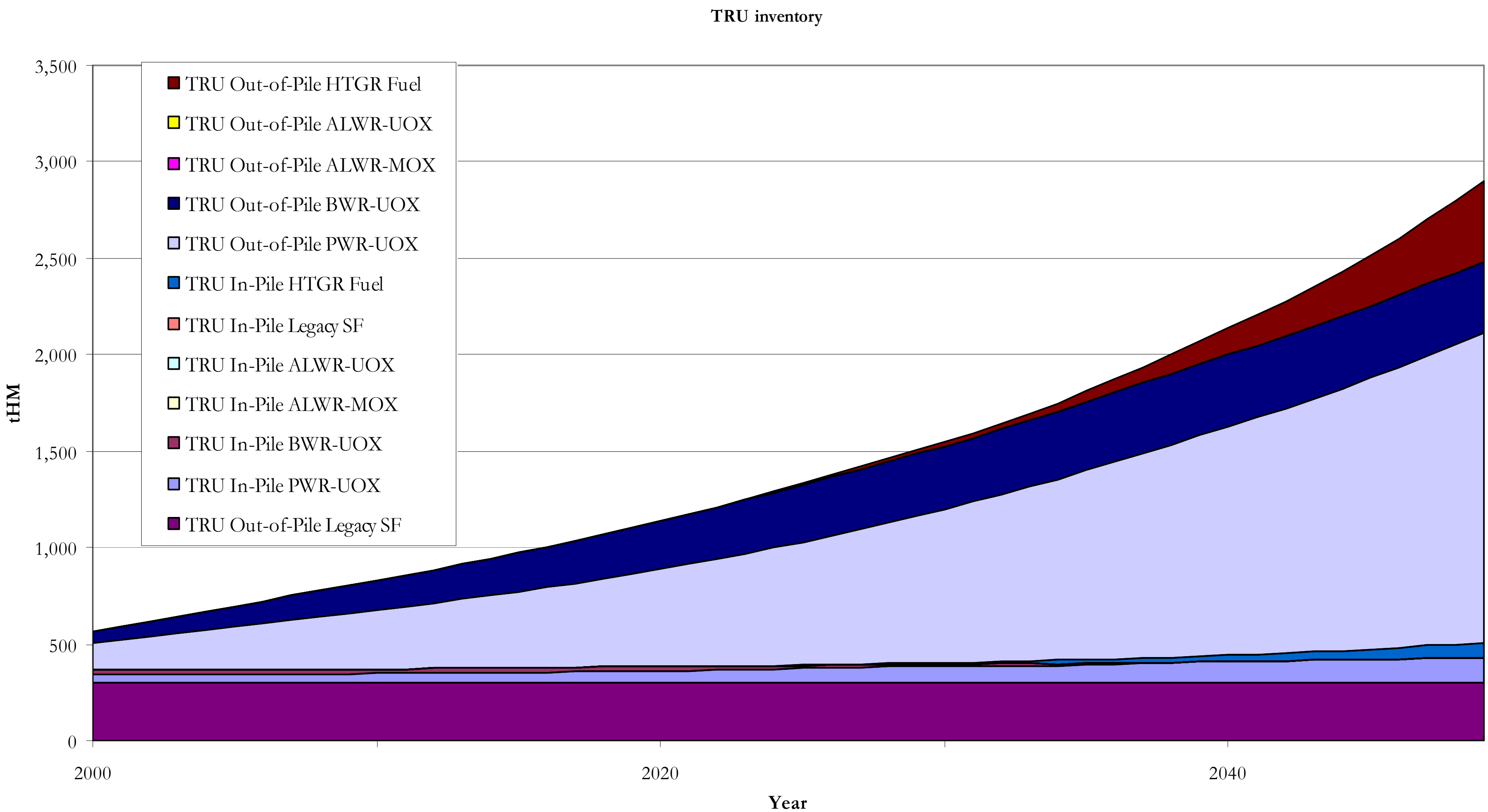
LWRs + HTGRs once-through operation

- **LWRs once-through operation for electricity demand only**
  - By mid-century
    - *190 000 tHM SF*
      - 2 400 tHM TRUs, including 2 180 tHM Pu
      - 1.5 million tons U_{nat} used during period of 2000-2050
        - On world-scale, this would become 5.9 million tU_{nat}
  - If also hydrogen energy demand should be delivered
    - *250 000 tHM SF, + 1 million tU_{nat} to be used*
- **LWRs + HTGRs once-through operation for electricity + hydrogen demand**

  But rapidly growing HTGR SF stock and enrichment services by end of century

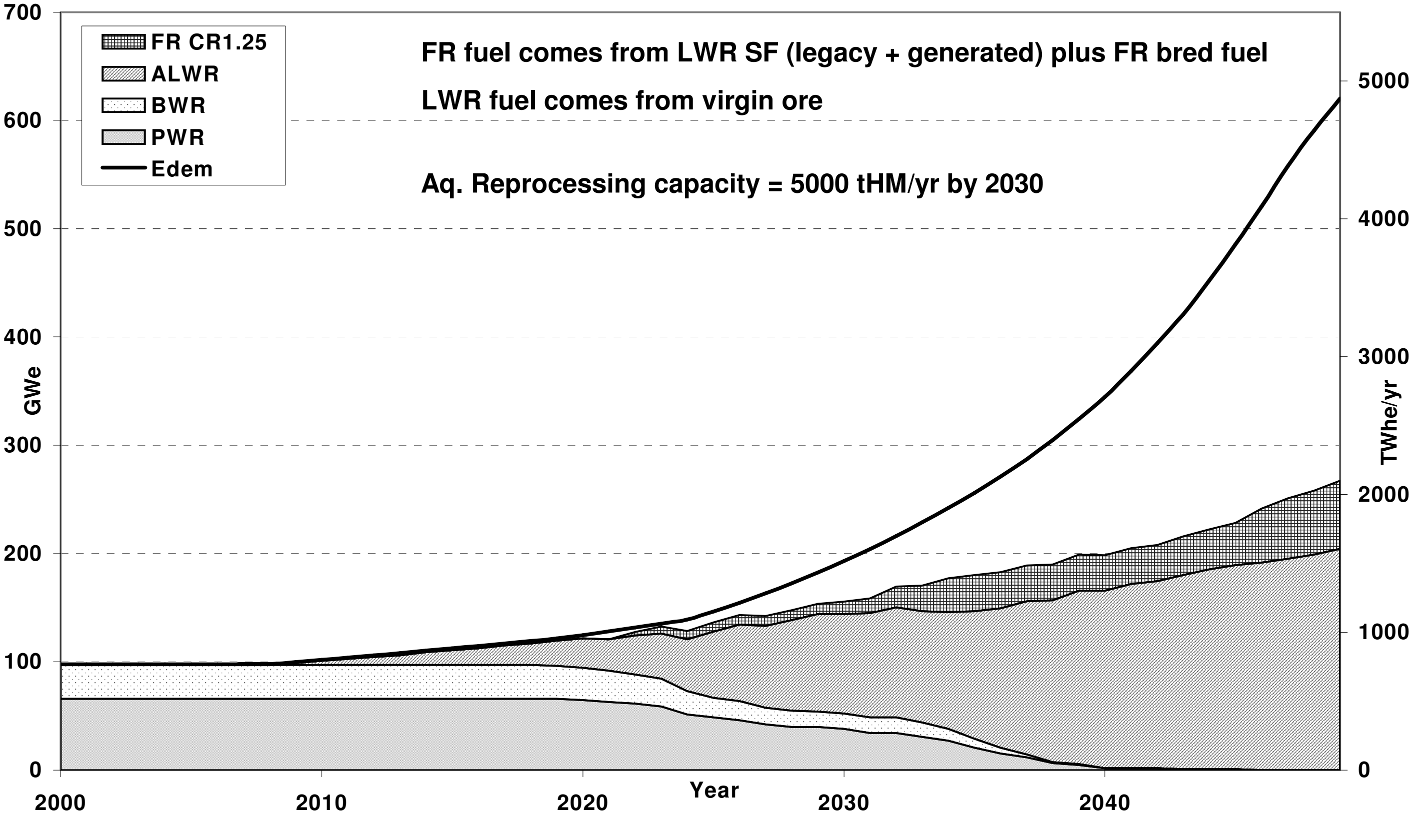
	ALWR	ALWR + HTGR
Energy demand	*Electricity*	*Electricity + hydrogen*
U_{nat} used 2000-2050 (10^6 tHM)	1.5	2.85
DU stock (10^6 tHM)	1.95	3.05
Enrichment (tSWU/yr)	31 200	152 400
Fabrication		
UOX (tHM/yr)	5 150	5 150
HTGR (tHM/yr)	-	3 500
SF at-reactor storage (tHM)	20 100	27 200
SF Interim storage (tHM)	171 200	174 500

TRU Inventory In-Pile and Out-of-Pile



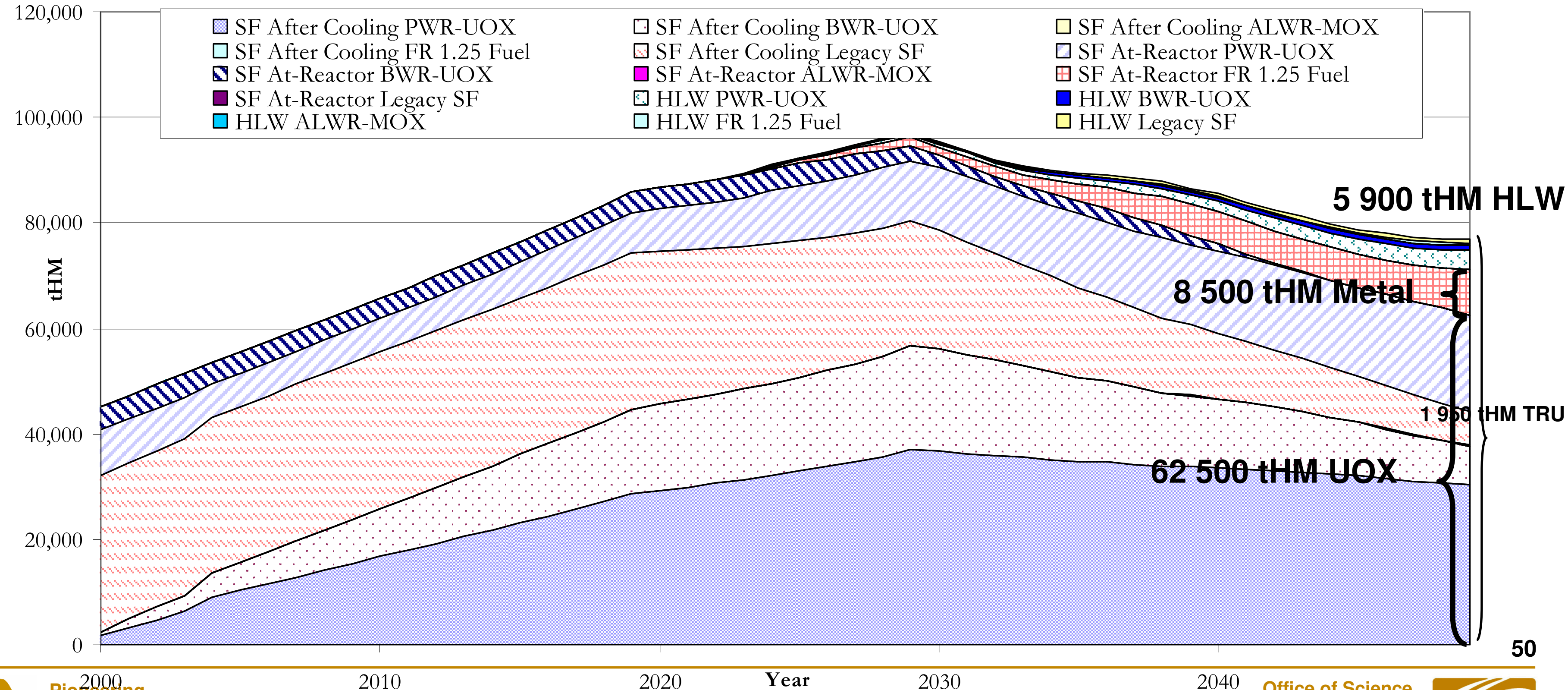
LWRs + FRs scenario

- Starting from today's existing LWR-park, and assuming CR = 1.25 for FRs, what is the maximum amount of energy that can be produced assuming LWRs for electricity use and FRs for hydrogen production?



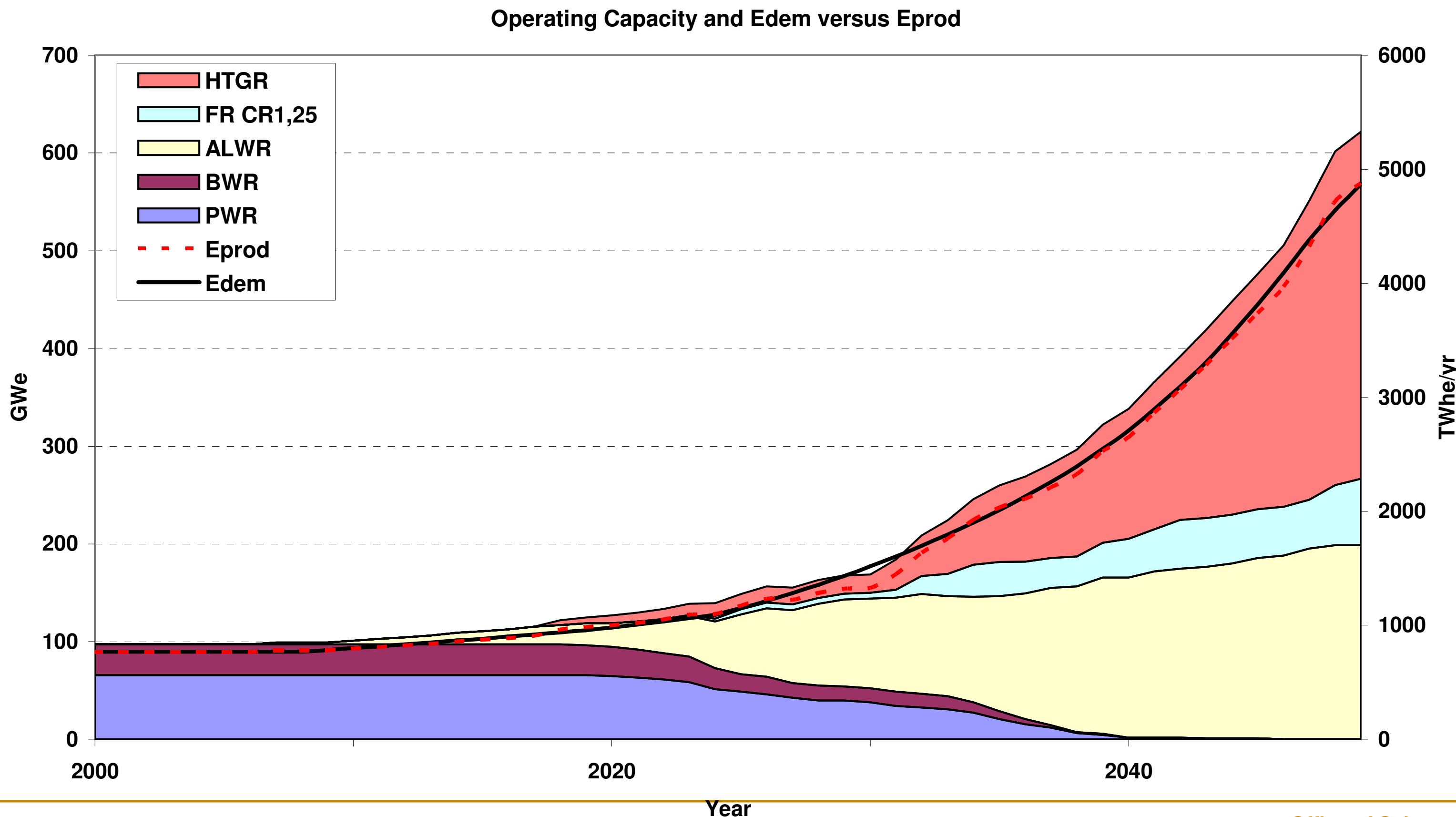
SF and TRU arising for LWRs + FRs scenario

- **LWR UOX Aq. Reprocessing:**
  - 2000 tHM/yr in 2020, + 3000 tHM/yr in 2030
  - 5 year cooling time
- **FR Metal Fuel Dry Reprocessing:**
  - Up to 1 200 tHM/yr
  - 5 year cooling time

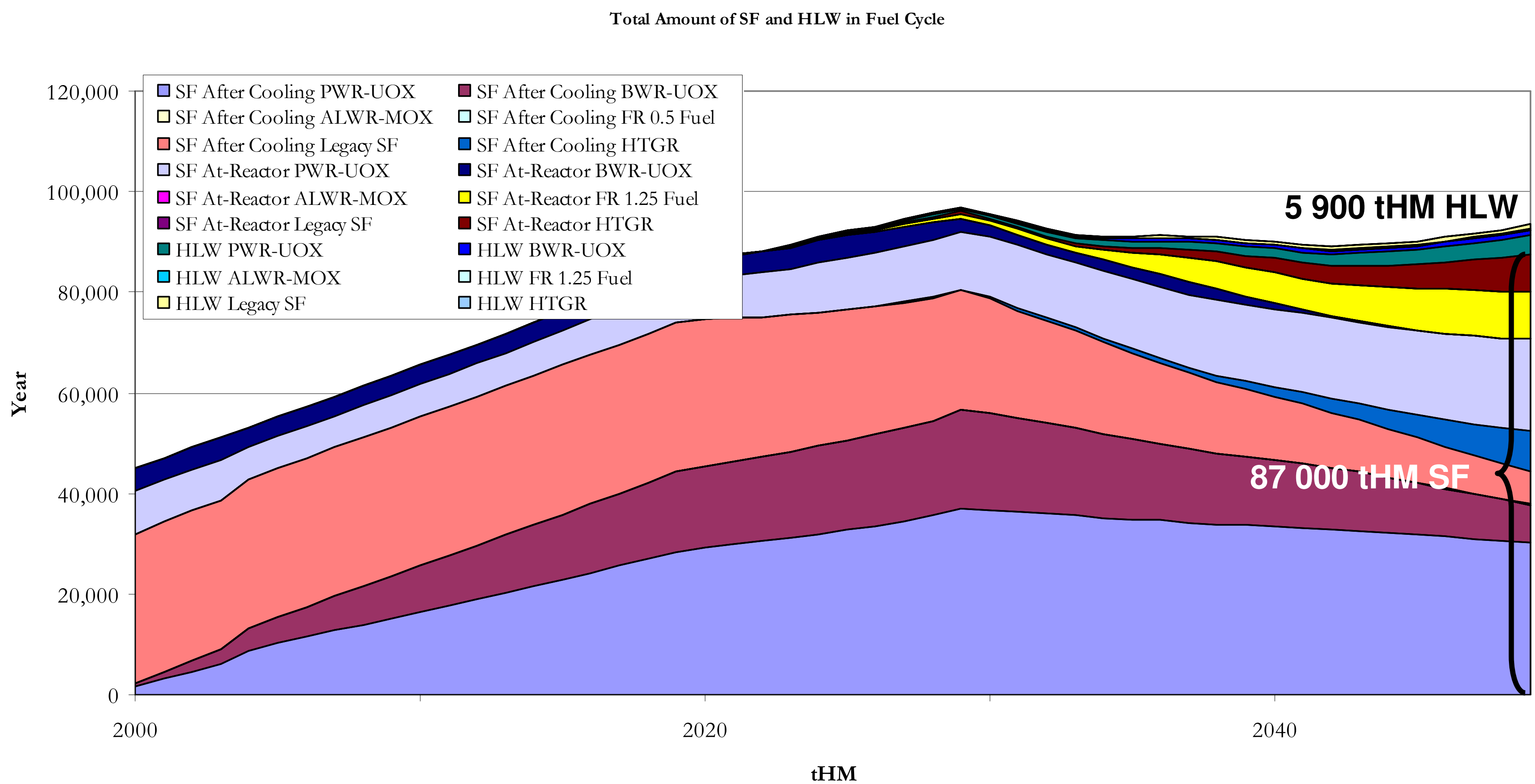


LWRs + HTGRs + FRs scenario

- LWRs for electricity production
- HTGRs + FRs (different CRs) for hydrogen production

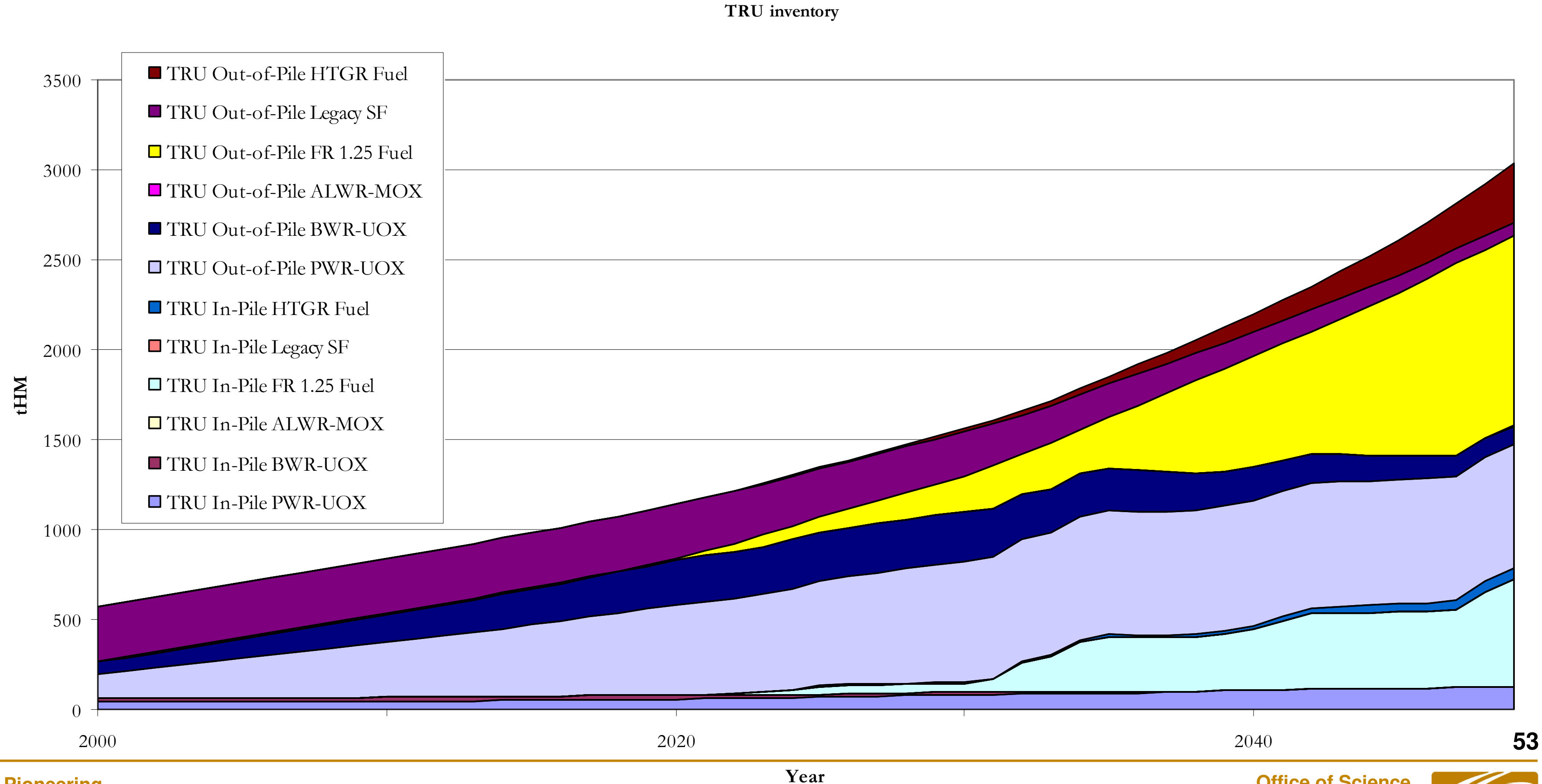


SF & HLW Inventory



TRU Inventory

- **In 2050**
  - CR = 1.25 TRU-amount = 2 250 tHM, 80 000 tHM SF
  - CR = 0.25 TRU-amount = 1 820 tHM, 88 000 tHM SF



Summary

- **A mix of**
  - 33 % LWRs once-through for electricity
  - 56 % HTGRs one-through for electricity/hydrogen
  - 11 % FR (CR 1.25) closed cycle for hydrogen

- **Succeeds to**
  - Meet demand for electricity and for hydrogen
  - Cap the SF stock at less than 100 000 tHM until 2050

- **But is it economic?**

Economics

- **Capital costs**
  - LWR 25.6 $/MWhe, i.e. 1 500 $/kWe overnight cost
  - HTGR 20.5 $/MWhe, i.e. 1 150 $/kWe
  - FR 37.7 $/MWhe, i.e. 2 000 $/kWe
  - WACC = 12 %, 17 years economic lifetime
- **O&M Costs**
  - 15 $/MWhe for all reactors
- **Fuel cycle costs**
  - HTGR particle fuel fabrication = 700 $/kgHM
  - LWR repro costs = 800 $/kgHM
  - FR repro costs = 1 100 $/kgHM; refab costs = 1 500 $/kgHM

$/MWhe	(A)LWR	(A)LWR + HTGR	(A)LWR + HTGR + FR CR 1.25
	Electricity	Electricity + hydrogen	Electricity + hydrogen + waste mgt
2020	50.1	49.9	55.3
2050	49.9	46.9	55.8

Conclusions Elec+H_2 for USA

- **Preliminary dynamic analysis showed:**
  - Electricity + hydrogen energy demand can be met by nuclear energy
    - *But, LWRs + FRs based scenario may be limited and need additional HTGRs to match fast growing energy demands*
    - *However, HTGR SF stock is growing rapidly and important front-end needs*
  - If waste management considerations are taken into account, then LWRs + HTGRs + FRs scenario allows to:
    - *Keep SF amount in fuel cycle below YM (technical) capacity to 2050*
    - *Reduce TRU inventory in fuel cycle by at least 20 % (mid century)*
    - *Keep energy cost increase less than 10 %*

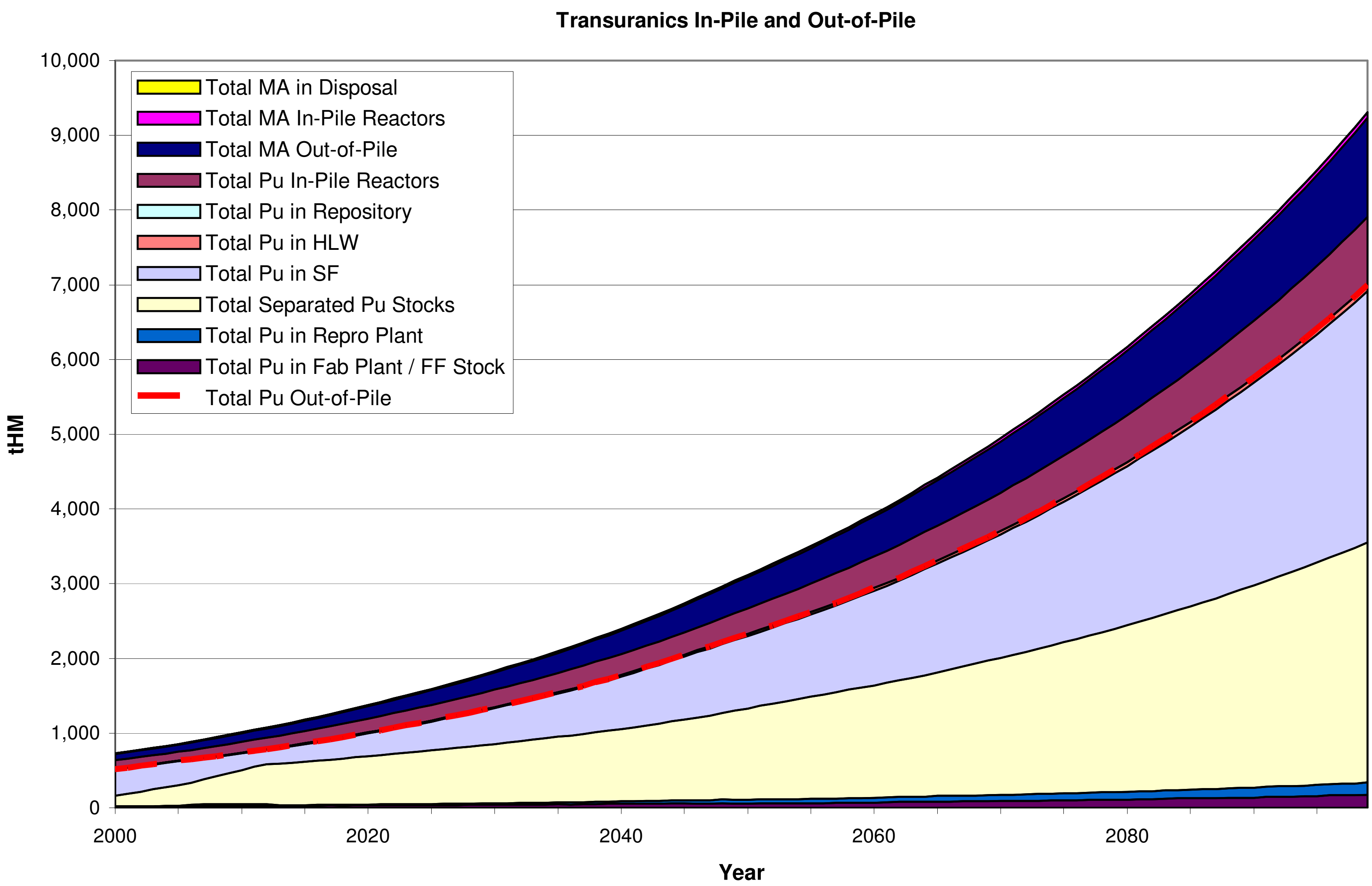
European Park Case *(preliminary results)*

- **Investigation of IMF-impact on European park**
  - Comparison with Pu(+Np) recycling
  - IMF as Pu deep burn in PBMR-type reactors
    - *BU 740 GWd/tHM*
  - Assumption of full reprocessing fuels, i.e. asking for maximum of
    - *MOX-ed reactors*
    - *IMF PBMRs*

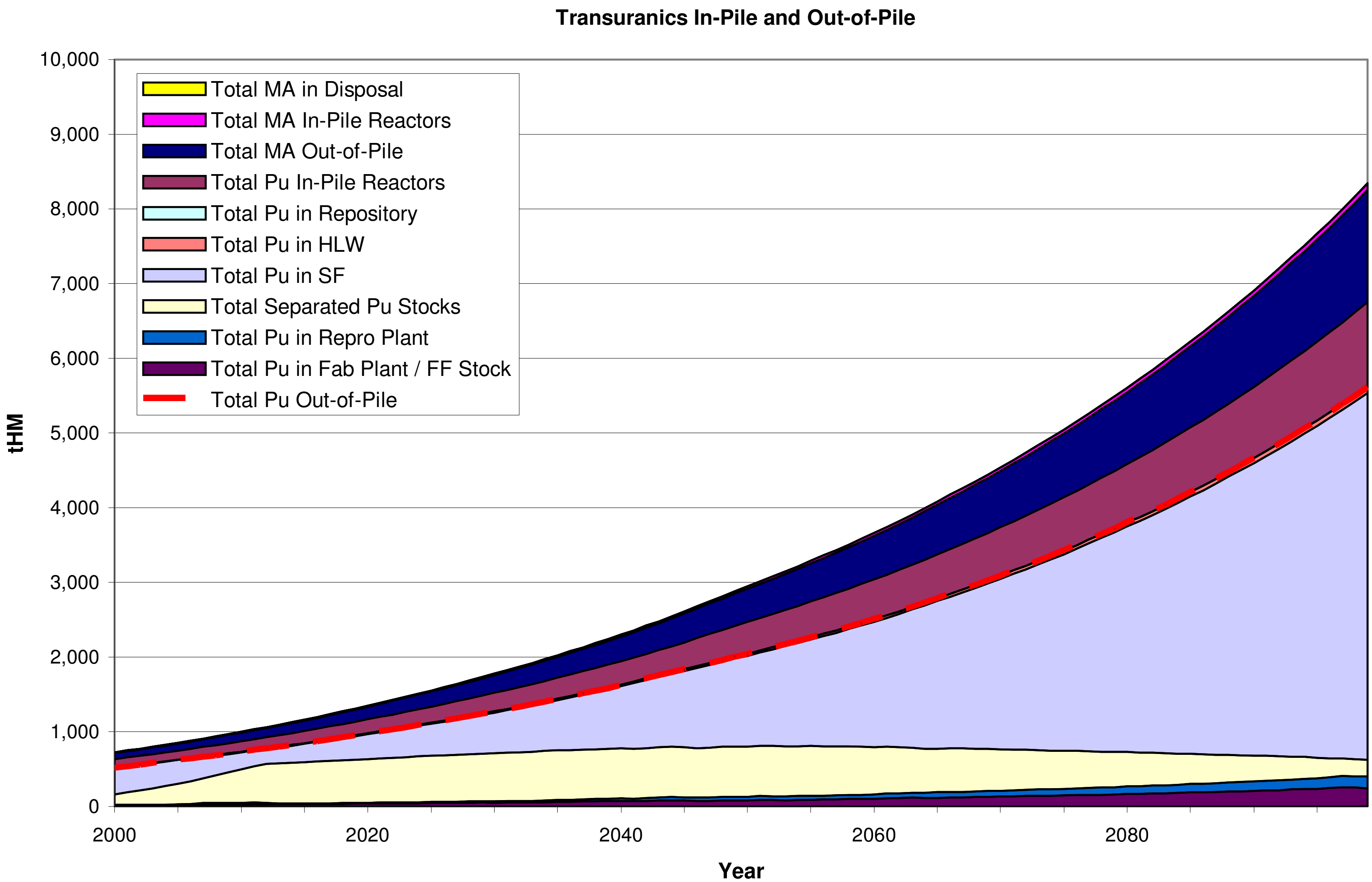
  - Nuclear energy demand grows 2%/yr after 2000.

  - Comparison of TRU inventory
    - *LWR-UOX + LWR-MOX (UOX all reprocessed; MOX not)*
    - *LWR-UOX + max LWR-MOX (UOX all reprocessed; MOX not)*
    - *LWR-UOX + max LWR-MOX + IMF (Pu from MOX to IMF)*

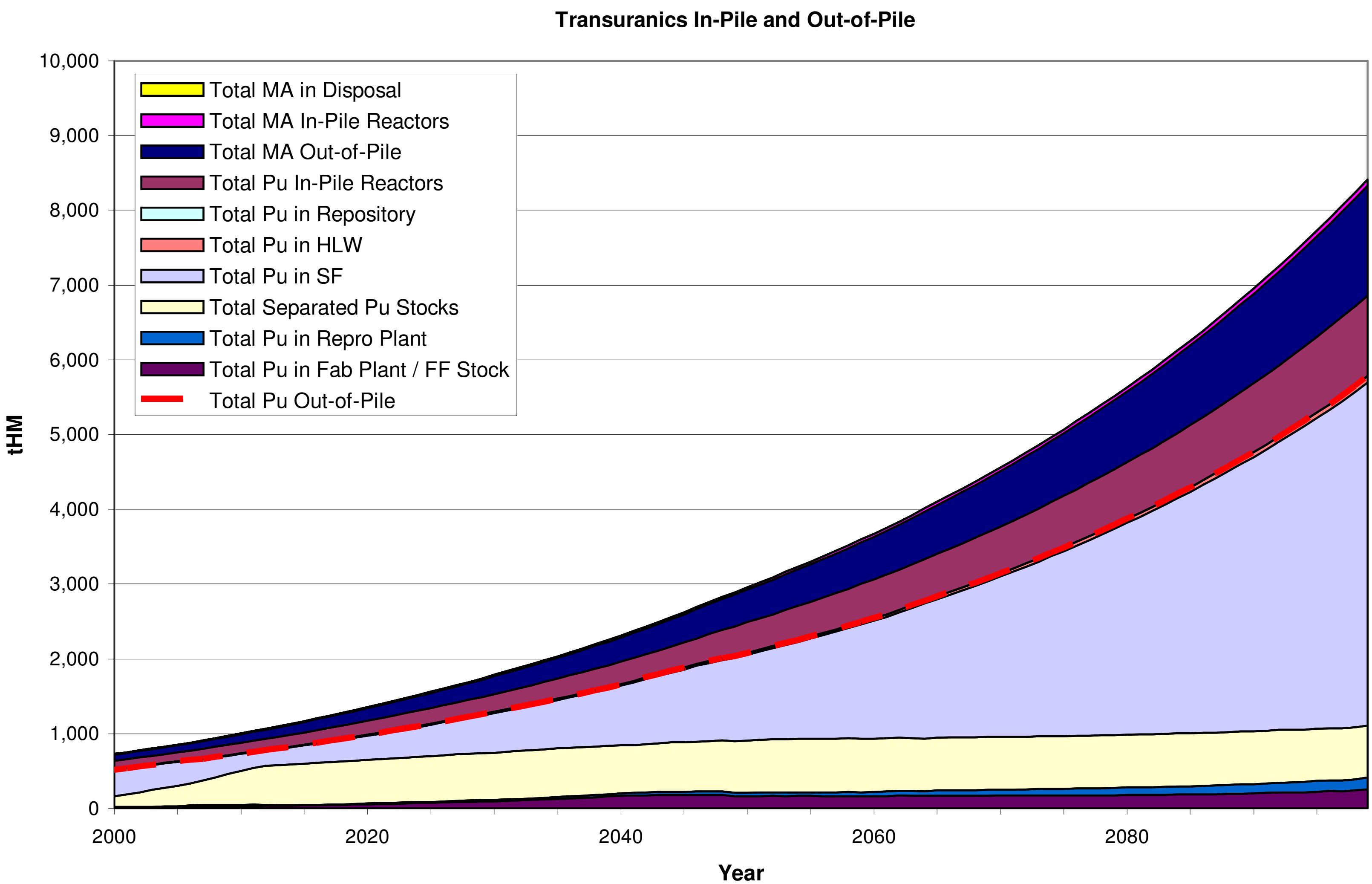
LWR-UOX + LWR-MOX (i.e. 36 %)



LWR-UOX + max LWR-MOX (i.e. 42 %)



LWR-UOX + max LWR-MOX + IMF (i.e. < 2 %)

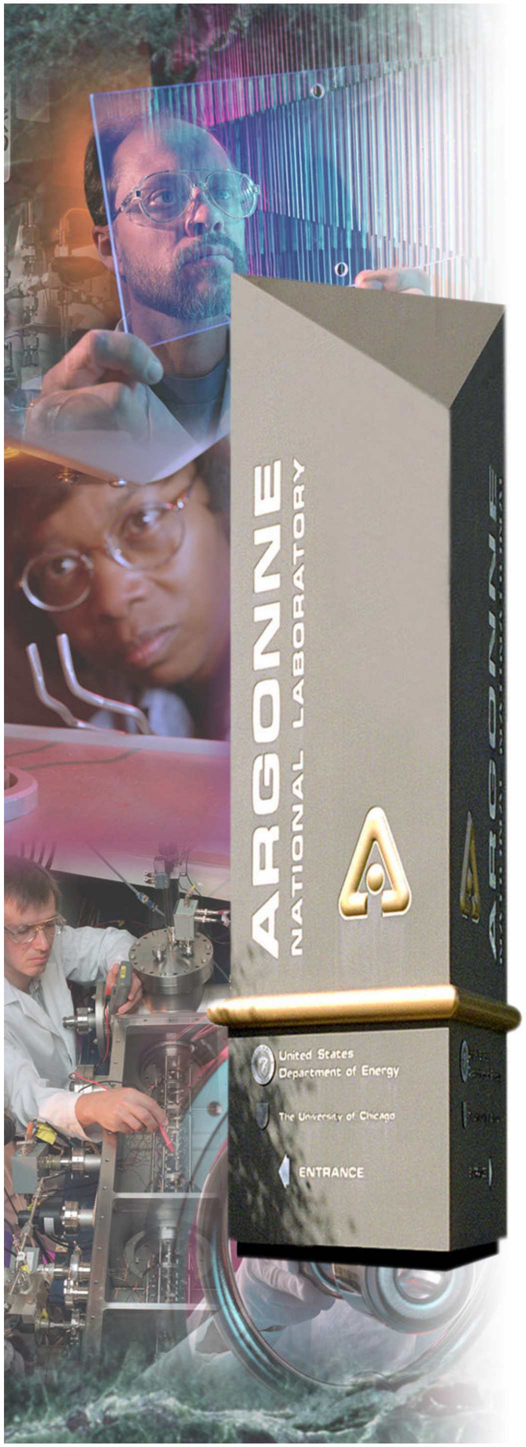


Conclusions

- **A new policy-informing nuclear energy system model has been developed**
  - Available through licence agreements (run/source code version)

- **Further development is planned on:**
  - Market penetration vs. non-nuclear sources
  - LCA
  - Waste management
  - Non-proliferation

- **Applications are ongoing**
  - USA: AFCI, Hydrogen, Gen-IV
  - Europe: NRG-Nl (Gas-cooled, IMF, …)
  - Korea: CANDU, …



Thank You

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